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Forest Growth Modelling and Prediction

Volume 2

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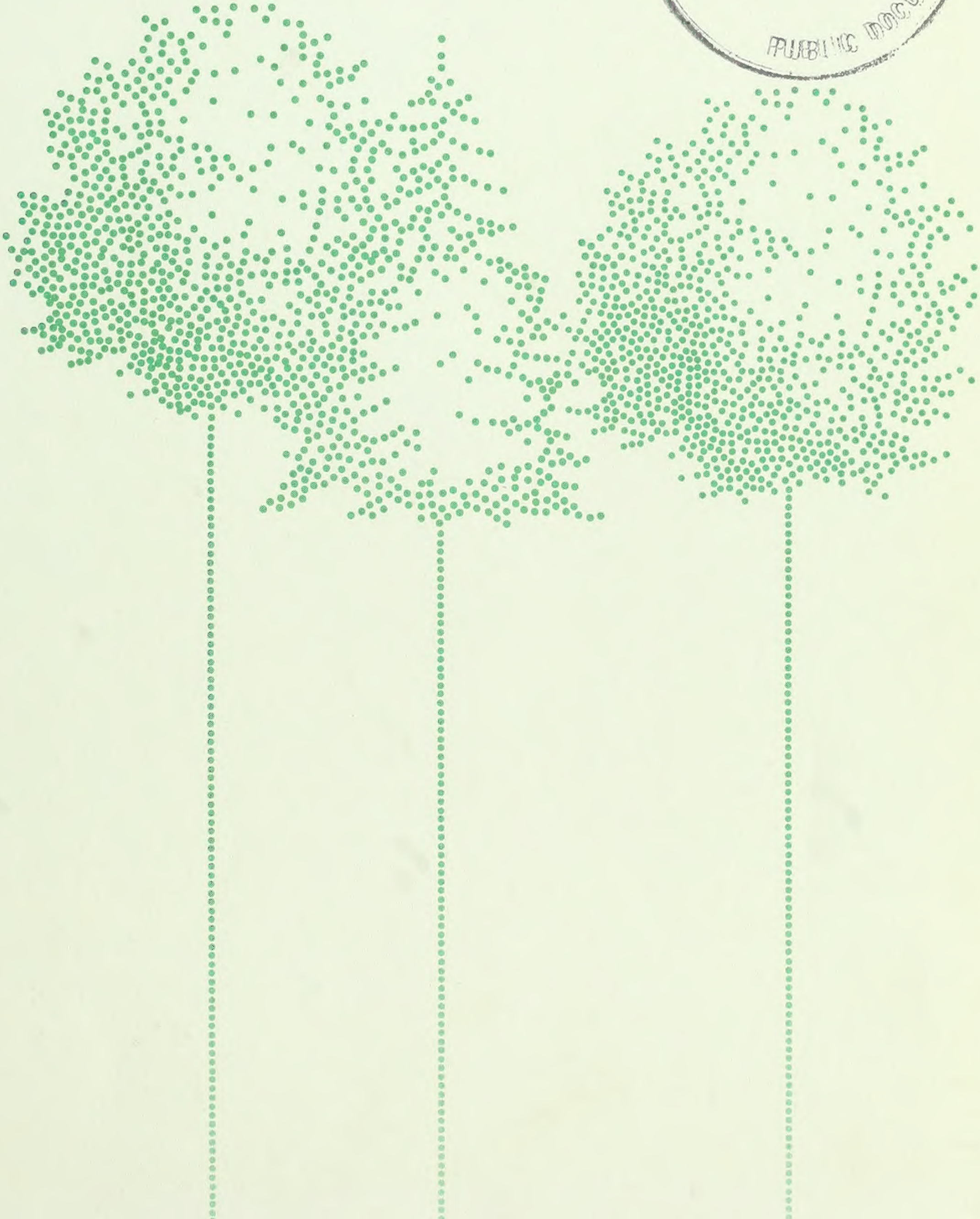

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Forest Growth Modelling and Prediction

Volume 2

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Evaluating Growth Models by Estimating A-line Location in Stocking Guides

Gary J. Brand and Rolfe A. Leary[1]

ABSTRACT. Evaluating a growth model is a complex task because many tests and comparisons can be made. It is especially difficult to empirically evaluate model performance for rare conditions such as dense stands. How accurately a model projects growth in dense stands can be evaluated graphically with the help of stocking guides. A stocking guide contains reference lines that graphically relate two stand density measures, number of trees and basal area, for several specific stand conditions. One of these reference lines (A-line or more recently referred to as AMD) represents the average maximum density stands achieve. The A-line can be estimated by a growth model and compared with the A-line in published stocking guides. We demonstrate this method by using an individual-tree, distance-independent growth model to estimate the location of the A-line for two species (jack pine and quaking aspen). Comparing the estimated A-lines with published A-lines highlights relations not easily identified in other types of evaluations.

INTRODUCTION

In the United States, stocking guides provide a simple basis for evaluating stand density using basal area and number of trees per unit area. Stocking guides, as first developed by Gingrich (1967), contain reference lines indicating three relationships to help guide management decisions. These have been designated A-line, B-line, and C-line. The B-line indicates combinations of number of trees and basal area at which trees start competing with each other and is based on the crown widths of open grown trees. The C-line is located at lower densities than the B-line such that, on average sites, 10 years of growth will produce a stand at the B-line. The A-line relates basal area to number of trees for stands near maximum densities and is always at higher stand densities than the B-line.

Ernst and Knapp (1985) renamed the reference lines in an attempt to clarify some of the confusion that developed as different methods were used to produce the various stocking guides now available. They designate Gingrich's A-line as the reference level of average maximum competition or more simply as the line of average maximum density (AMD). The B-line is the reference level of no competition. They do not identify the C-line. In this paper we are only concerned with the line of average maximum density and will refer to it by its traditional name

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(A-line) to be consistent with the published stocking guides we will refer to.

Gingrich (1967) developed the A-line from natural, undisturbed stands thought to be at maximum density and data in Schnur's (1937) stand table. Gingrich claimed that the A-line defines a relation between number of trees and basal area toward which, "in the absence of cutting or other disturbances," stocking moves, "whether currently above or below ... it". The A-line, as conceived by Gingrich, represents a long-term dynamic equilibrium of stand properties. Stands can get above the A-line during periods of favorable weather, but in the longer term they should approach this equilibrium. The A-line in stocking guides should not be confused with the self-thinning framework (Yoda et al. 1963, White and Harper 1970, White 1981) which relates mean stem mass or volume to stand density. At low densities, and advanced ages, the self-thinning or competition-density rule postulates a maximum mass or volume per tree. The A-line, however, should eventually show a decrease in basal area as number of trees decreases. More specifically, when there is only one tree per acre remaining, the basal area can only be as large as the basal area of the largest possible tree and this is certainly less than the basal areas that stands achieve.

We contend, then, that a growth model applied to pure, even-aged stand conditions should:

1) Predict that basal area and number of trees converge toward a well defined line.

2) Produce a line whose shape and location are reasonably consistent with the empirically derived A-line for a compatible stocking guide.

3) Produce a line that has a maximum basal area.

If the model doesn't meet the first and last criteria it has failed two of the many tests a model can be subjected to. Failure to achieve the second criterion indicates that there are two conflicting hypotheses. It may not be clear whether the growth model is inappropriate, the stocking guide is wrong, or both.

METHODS

Leary and Stanfield (1986) added direction field elements to stocking guides to help estimate future stand conditions. A direction field element is a line segment that shows how the number of trees and basal area of a stand will change. The periodic change can either be shown by field observations or projected by a model. Usually the period is 5 or 10 years. In this analysis we plotted 10 consecutive periods of 3 years each for many starting conditions on the stocking guide. The consecutive periods were placed end to end to produce a "trajectory" of projected number of trees and basal area for each initial condition. Trajectories were produced for jack pine (Pinus banksiana Lamb.) with a site index of 60 feet and aspen (Populus tremuloides Michx.) with a site index of 65 feet.

We used the STEMS/TWIGS growth model (Miner et al. In press) to predict change in number of trees and basal area. STEMS/TWIGS is a distance-independent, individual-tree, model (Munro 1974) developed for tree species in the North Central region of the United States. Site index, stand basal area, mean stand diameter, and the tree characteristics of species, diameter, and crown ratio are the explanatory variables used to predict growth and mortality. Because the projected stand is represented by a list of trees, we created a diameter distribution for each stem density and basal area combination. Diameter distributions for aspen (Baker 1923, Brown and Gevorkiantz 1934) and jack pine (Eyre and LeBarron 1944) stands are typically unimodal. A normal distribution often adequately describes the diameter distribution of even-aged stands (Gingrich 1967, Lorimer and Krug 1983). Therefore, for each desired combination of basal area and number of trees, a tree list was generated that had a normal frequency distribution of tree diameters. The standard deviation of the distribution, s, was calculated using a function derived by Lundgren (1981) for red pine (Pinus resinosa Ait.):

$$s = a D e^{b D}$$

where D is the quadratic mean diameter and a, b are coefficients. The red pine coefficients determined by Lundgren (1981) were used for jack pine (a=.376, b=-.093); the coefficients for aspen (a=.368, b=-.053) were obtained by fitting the equation to stand table and research plot data.

RESULTS AND DISCUSSION

The location of the A-line as estimated by the growth model vividly highlights differences between predictions and the relations identified by a stocking guide; these discrepancies are not evident when the model is evaluated in other ways. For example, an earlier evaluation of the Lake States STEMS/TWIGS model (Holdaway and Brand 1986) showed that jack pine and aspen predictions compared well with a set of independent observations of stand change. Yet for both of these species the model falls short in meeting at least one of the three criteria set forth above.

Projected basal area and numbers of trees for jack pine definitely converge toward a dynamic equilibrium, especially at the lower numbers of trees (Figure 1). Trajectories in figure 1 represent 30-year projections with an arrow marking the end of each 3- year period.[2] For example, one trajectory starts at 500 trees per acre with 80 square feet of basal area per acre and ends 30 years later (the 10th arrow) at about 290 trees per acre with 115 square feet per acre. At high densities both basal area and number of trees decrease (e.g. 500 trees per acre with 160 square feet per acre). Although the first criterion, convergence, is evident, the shape and location of the trajectories'

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[2] Leary and Stanfield (1986) developed a direction field for jack pine using a previous version of the STEMS/TWIGS model. Therefore, their dynamic stocking guide is different than the one presented here.

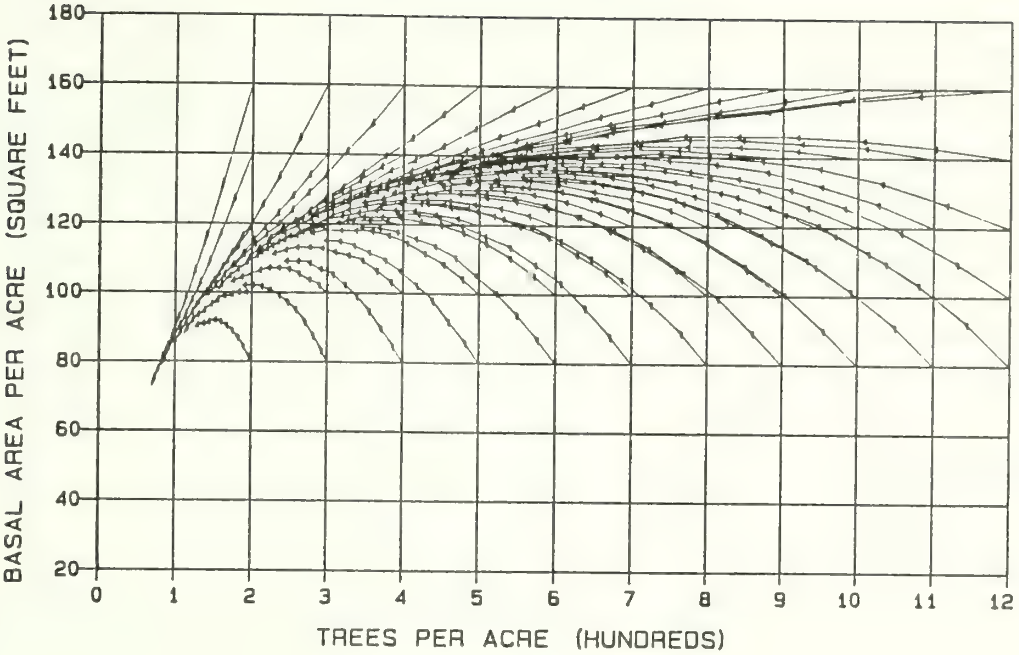

Figure 1. Thirty-year trajectories for jack pine, site index 60. Based on predictions from STEMS/TWIGS.

convergence are different than Benzie's (1977) A-line (Figure 2). Benzie based the A-line on yield tables for well-stocked jack pine (Eyre and LeBarron 1944) supplemented with data from research plots. For poletimber stands the A-line represents about 85 percent stocking and for sawtimber stands 100 percent stocking of normal yield tables. Using 100 percent of the yield table values for poletimber stands would bring these A-lines closer together but would not rectify their differences in shape. Part of the difference in shape is related to when the model's A-line reaches a maximum basal area. Although the estimated A-line does reach a maximum, thus meeting the third criterion, the maximum occurs at a number of trees larger than would be expected.

Although aspen projections do converge to a dynamic equilibrium, the rate of convergence is slow when number of trees is large (Figure 3), making it difficult to determine exactly where the predicted A-line should be. In addition, the trajectories below the region of convergence do not have the expected curvature. We would expect these trajectories to be convex toward the region of convergence (more rapid decrease in number of trees as the A-line is approached). Competition should become more intense as a stand nears the A-line, causing greater mortality, and therefore the convex shape. The general shape of the model's A-line, however, is similar to the A-line (Figure 4) developed by Perala (1986). The two lines are close between 100 and 400 trees per acre but diverge for larger numbers. Perala developed the A-line from an aspen yield table (Brown and Gevorkiantz 1934) and confirmed it with an aspen thinning model (Perala 1978). The model clearly indicates a

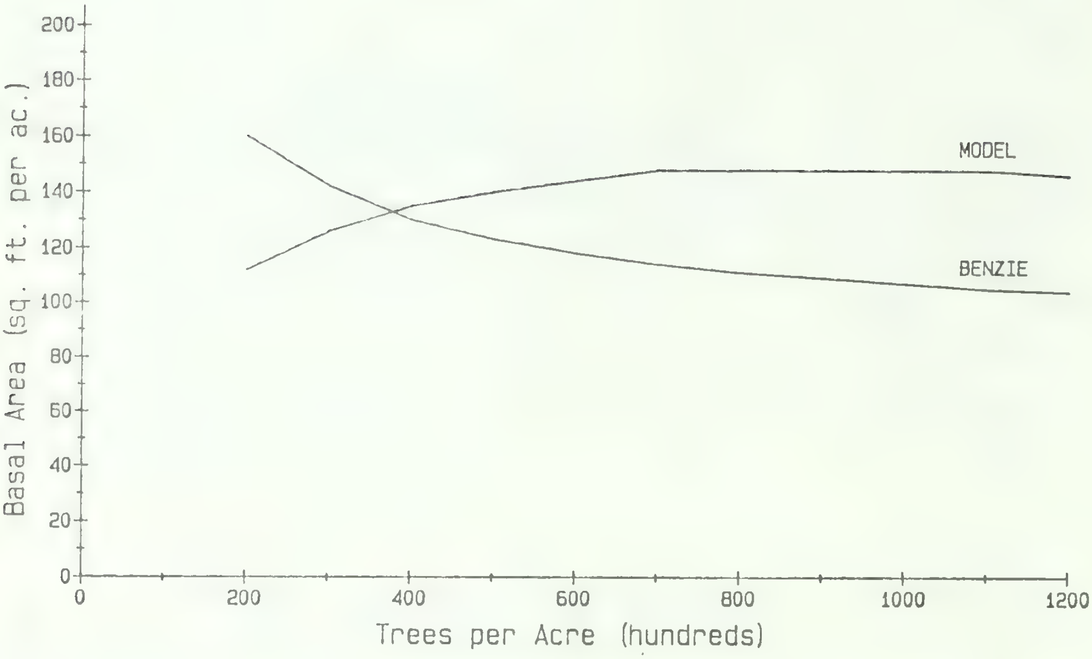

Figure 2. A-line from Benzie (1977) and A-line estimated from the convergence of the trajectories in Figure 1.

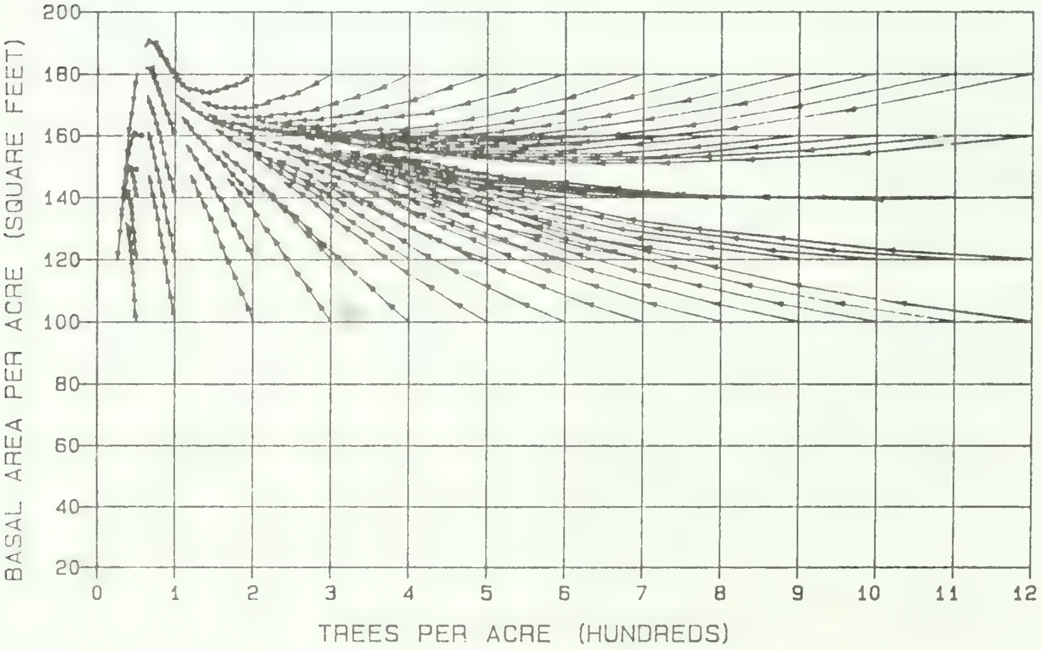

Figure 3. Thirty-year trajectories for quaking aspen, site index 65. Based on predictions from STEMS/TWIGS.

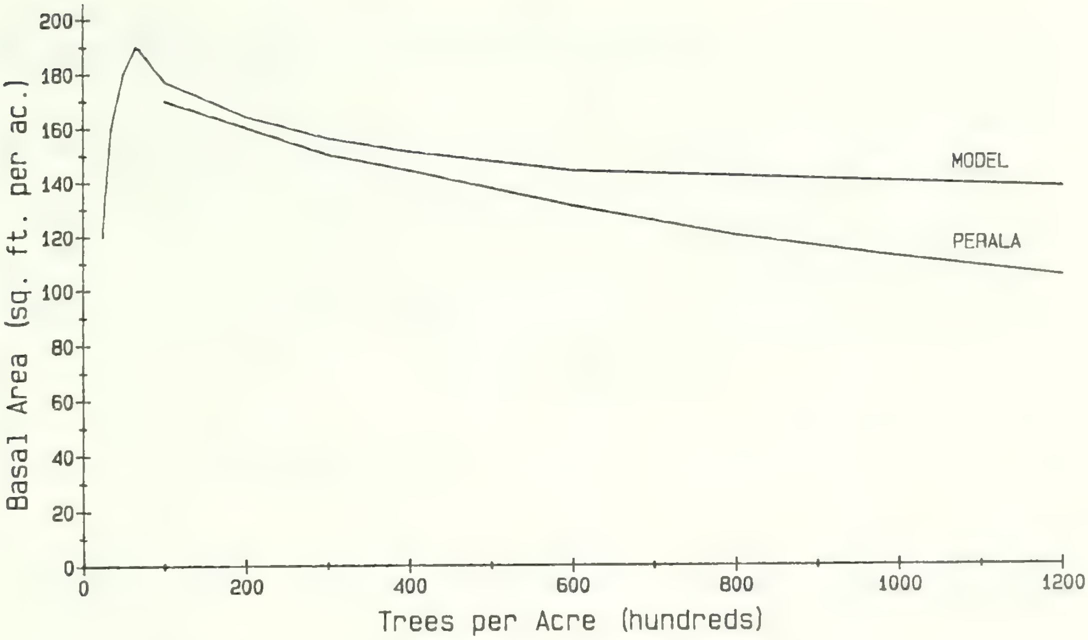

Figure 4. A-line from Perala (1986) and A-line estimated from the convergence of the trajectories in figure 3.

maximum basal area of about 190 square feet per acre at about 70 trees per acre.

Because data are often scarce for extreme conditions (i.e. dense or sparse stands, high or low sites, large or small trees), it is difficult to empirically evaluate models under these conditions. We have demonstrated a method for evaluating model behavior in dense stands that does not require repeated measurements from dense stands. The method provides a basis for identifying conditions where model predictions should be avoided or at least explored further because the results do not match the hypothesis of the stocking guide. In our examples these are dense jack pine stands with fewer than 400 trees per acre and dense aspen stands with more than 600 trees per acre.

ACKNOWLEDGMENT

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RELATIVE GROWTH RATE: AN ANALYTICAL TOOL FOR GROWTH AND YIELD ANALYSIS

Roland G. Buchman and John W. Benzie[1]

Abstract. The relative growth rate (RGR), introduced by Blackman as a plant's efficiency index of dry weight production, has potential as an analytical tool for growth and yield analysis. Its application is not restricted to either dry weight or to individual plants. The relation of RGR to conventional forest application measures such as stand basal area or tree diameter is described. RGR's use in modelling and describing within-stand dynamics is illustrated. RGR is easy to convert to application measures and easy to calculate; it adjusts growth for initial tree or stand conditions.

INTRODUCTION

Blackman (1919), compared the increase in dry weight of plants, particularly annuals, to money accumulating compound interest. He called the rate of interest the "efficiency index" of the plant's dry weight production, representing the efficiency of a plant as a producer of new material. He described the growth of annual plants as:

$$W_1 = W_0 e^{rt} \qquad (1)$$

where w_1 = final weight, w_0 = initial weight, r = rate of increase (later named the relative growth rate, RGR), t = the length of the growth interval, and e = the base of natural logarithms.

However, RGR is not constant for the life of a plant; growth is affected by the plant's external conditions and by its stage of development. For example, a tree's RGR is affected by its competition and its proportion of basal area in structural material. However, the assumption of constancy isn't needed for calculating RGR (Evans 1972). Redefining w_1 and w_0 in equation (1) to be the weight at the end and at the beginning, respectively, of some growth interval provides for these RGR changes and for calculating RGR for a portion of a plant's life.

RGR has been widely used for plant growth analysis in agriculture and botany. Hunt (1982) points out that RGR is especially useful in comparing species or treatments on a uniform basis. He expanded its scope from dry weight to fresh weight, volume, area, and number of individuals as suitable measures; RGR can be applied to plant communities as well as to individual plants.

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Recent texts on forest growth and yield (for example, Davis and Johnson 1987; Clutter et. al. 1983) do not include RGR as an analytical tool. Nor does it appear in Assman's (1970) compendium on forest growth and yield. RGR has received little attention in forestry literature perhaps because of the longevity and size of trees (Brand et al. 1987).

However, our experience indicates RGR would be a useful analytical tool for forest growth and yield analysis. Our purpose here is to reintroduce RGR and suggest applications for it in forest growth and yield analysis.

RGR AND OTHER GROWTH AND YIELD MEASURES

Based on equation (1) RGR is readily calculated:

$$\mathrm{RGR} = \ln\,(W_1/W_0)/t \qquad (2)$$

where ln indicates natural logarithm and the other symbols are as previously defined.

Tree and stand illustrations in this paper are based on basal area. Thus, the RGR under consideration is:

$$\mathrm{RGR} = \ln\,(BA_1/BA_0)/t. \qquad (3)$$

RGR adjusts the plant's or the stand's growth or size after some growth interval for the "production base" at the start of that interval. The production base, as used here, consists of the entire basal area including the non-productive support tissues. The relation of RGR to growth for an increasing production base is shown in Figure 1.

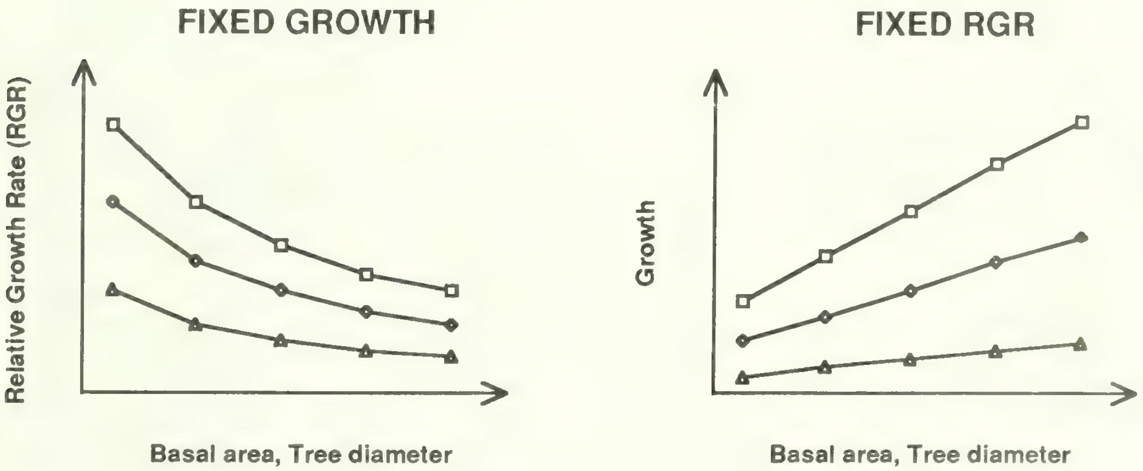

Figure 1. The relation of RGR to growth for increasing plot basal area per unit area or tree diameter. Fixed growth on an increasing base leads to declining, concave upwards converging RGR lines. Fixed RGR corresponds to linear diverging growth increases.

The measures of forest growth and yield commonly used by silviculturists and forest managers are "state" or "application" measures including basal area growth and total basal area, diameter growth, and average diameter. In contrast, RGR is an "analytical" measure, useful for developing models or understanding the dynamics of trees and stands. However, application measures can be readily calculated from RGR:

$$\text{Future basal area} = BA_0\, e^{RGR\ t} \qquad (4)$$

$$\text{Annual basal area growth} = BA_0(e^{RGR\ t}-1)/t \qquad (5)$$

$$\text{Future diameter} = DBH_0[e^{(RGR\ t)/2}] \qquad (6)$$

$$\text{Annual diameter growth} = DBH_0[e^{(RGR\ t)/2}-1]/t. \qquad (7)$$

Diameter calculations require division by 2 in the exponent because RGR is obtained from tree basal area. RGR in equations (4) and (5) is for basal area per unit area; RGR in equations (6) and (7) is for basal area per tree.

ANALYTICAL USES OF RGR

RGR can be a useful analytical tool for modelling stand and tree growth, evaluating treatments such as thinning levels or thinning methods, and describing within-stand dynamics. We will illustrate these uses with data from a thinning study in a red pine plantation in northeastern Minnesota. Site index of the plantation is 70 feet at age 50. Basal area was about 180 square feet/acre at age 43, the time of the first thinning (thinning was done after the growing season for the age mentioned). Thinning methods were from above, from below, and a combined thinning with half the basal area from above and half from below for five residual stand densities ranging from 30 to 150 square feet of basal area per acre.

TREE AND STAND MODELS

The first example relates RGR to the basal area of unthinned stands (Figure 2). Basal area accounted for 60 percent of RGR variation, indicating the ability to predict RGR from basal area and to provide estimates of future stand basal by entering that RGR in equations (4) and (5).

RGR is also highly correlated with the residual basal area of thinned stands (Figure 3). Basal area accounted for 97 percent of the RGR variation for stands between ages 44 and 48 years and 87 percent between ages 63 and 68 years, indicating the ability to predict RGR and to provide estimates of future basal area after thinning by substituting a predicted RGR in equations (4) and (5). Also note that the effect of thinning method became much more pronounced at ages 63-68 and reduced the explained variation from 97 to 87 percent. The smoothed RGR data from Figures 2 and 3 converge.

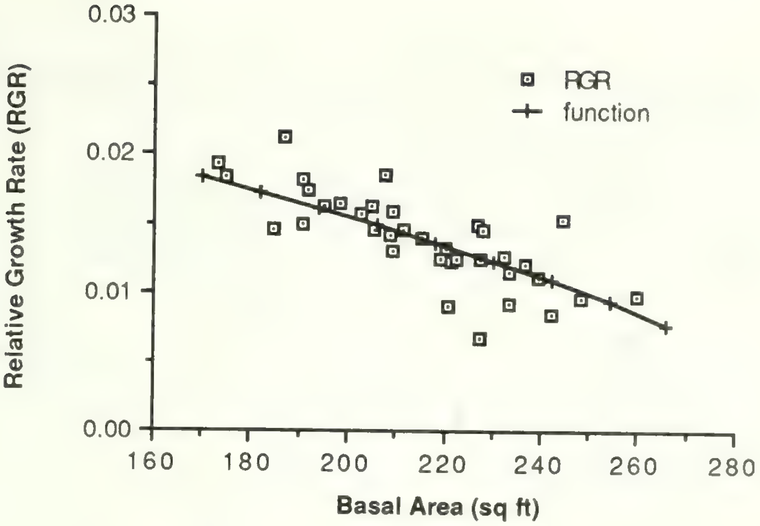

Figure 2. The relation of RGR to basal area for nine unthinned red pine plots with four observations per plot (line is smoothed RGR data).

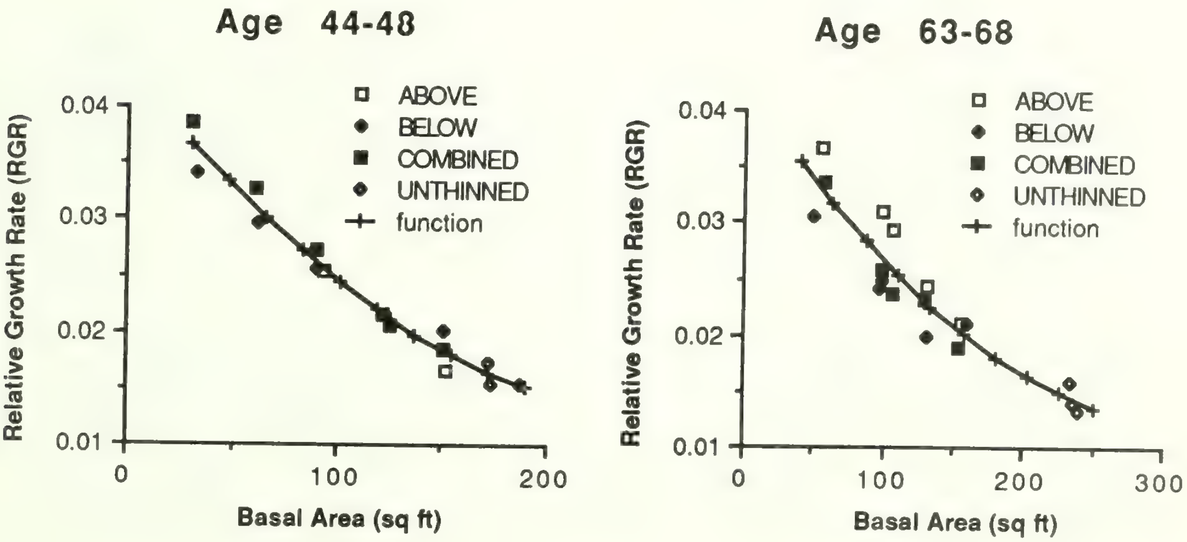

Figure 3. The relation of RGR to residual basal area for three methods of thinning (each observation is the average for three plots) and the smoothed RGR data.

For our final modelling example, we calculated the average tree RGR for 1-inch tree diameter classes and related RGR to the quadratic mean diameter (QMD) of each class within each stand's basal-area level (Figure 4). Only stands with the combination thinning - above and below - were used. The results show that RGR's by diameter class within the most heavily thinned stands shown (residual density of 60 square feet of basal area per acre) exceed those of all other thinning levels. RGR's for the unthinned stands were the lowest; those for the other stand densities were in the expected positions.

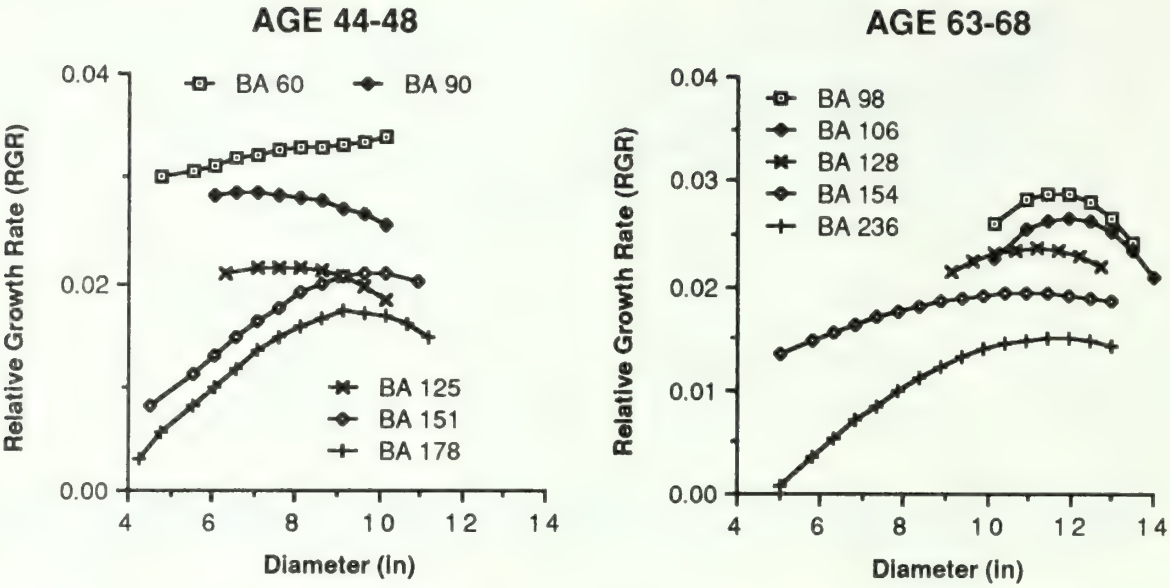

Figure 4. RGR by tree diameter class for five residual stand densities at ages 44-48 and 63-68.

The RGR data for the stands and for the tree diameter classes (Figures 2, 3, and 4) suggest that RGR will be useful in developing growth and yield models because of the consistency among the response curve shapes and the relative position of these curves. RGR can ultimately provide estimates of future growth and yield through the use of equations (4), (5), (6) and (7).

WITHIN-STAND DYNAMICS

Our first example in this section shows the use of RGR when interpreting the effects of thinning methods and thinning levels. The results for residual stand density levels of 60 square feet and the 120 square feet immediately after the first thinning and for the same stands 20 years later show the effect of thinning method and thinning level (Table 1).

Table 1.--Stand RGR and quadratic mean diameter (QMD) for two ages, two thinning methods, two thinning levels, and for uncut plots.

Thinning		Ages: 44-48		Ages: 63-68	
BA Level (sq ft/ac)	Method	RGR	QMD (in.)	RGR	QMD (in.)
60	above	.0260	7.2	.0294	10.3
60	below	.0298	10.0	.0242	13.9
120	above	.0220	7.5	.0226	9.5
120	below	.0218	9.1	.0200	11.4
--	uncut	.0160	8.2	.0135	9.8

The stands thinned to 60 square feet of basal area at 43 and 48 years had grown to 98 square feet at age 62. Residual trees in the stands thinned from above had a higher RGR 15 years after the second thinning than immediately after the first thinning; the stands thinned from below, where selection favored the larger trees at ages 43 and 48, had a lower RGR. RGR changed little in stands thinned to 120 square feet basal area at 43, 48, and 58 years of age; RGR of uncut stands decreased during the 20 years.

The contrast between thinning methods becomes more obvious when we look at the diameter-class RGR's within the 60-square-foot stands (Figure 5). Thinning from above resulted in higher RGR's for all diameter classes at ages 63-68 than at ages 44-48; smaller trees had gained the most. All trees received crown release, and some trees probably had less root competition as well. The smaller trees apparently received more release above ground and, perhaps, below ground than the larger trees and probably had greater capacity to respond after 15 years.

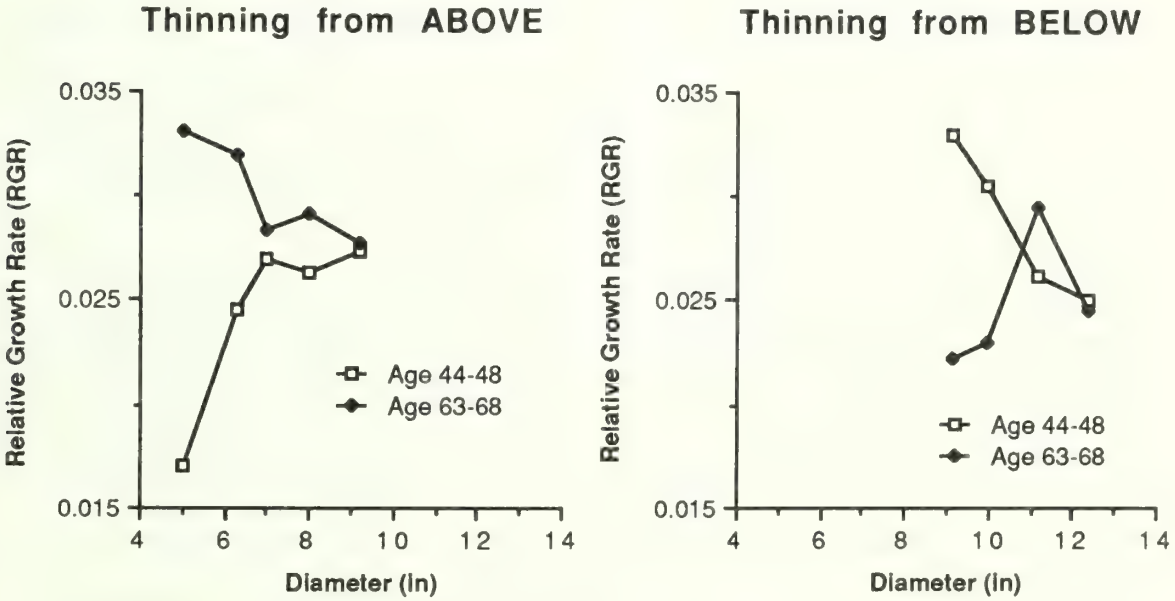

Figure 5. The relation of RGR to tree diameter for age 43 thinning from above and thinning from below to 60 square feet residual basal area (basal area increased to 98 square feet by age 62).

Thinning from below produced an RGR response at ages 44-48 that was similar to the response 20 years after the first thinning from above (Figure 5). The smaller trees in the stand thinned from below at ages 43 and 48 declined in RGR 15 years later (ages 63-68).

Our second example shows the use of RGR in describing within-stand dynamics during the development of competition and self-thinning. Two tree diameter-class profiles for the unthinned stands are shown, one at ages 44-48 with 178 square feet of basal area and the other for the same stands at ages 63-68 with 236 square feet per acre (Figure 6a). For the same diameter classes, RGR declines at the higher stand basal area, reflecting the increase in competition. This reduced RGR by diameter size can be readily translated into an expected increase in tree mortality (Buchman et. al. 1983).

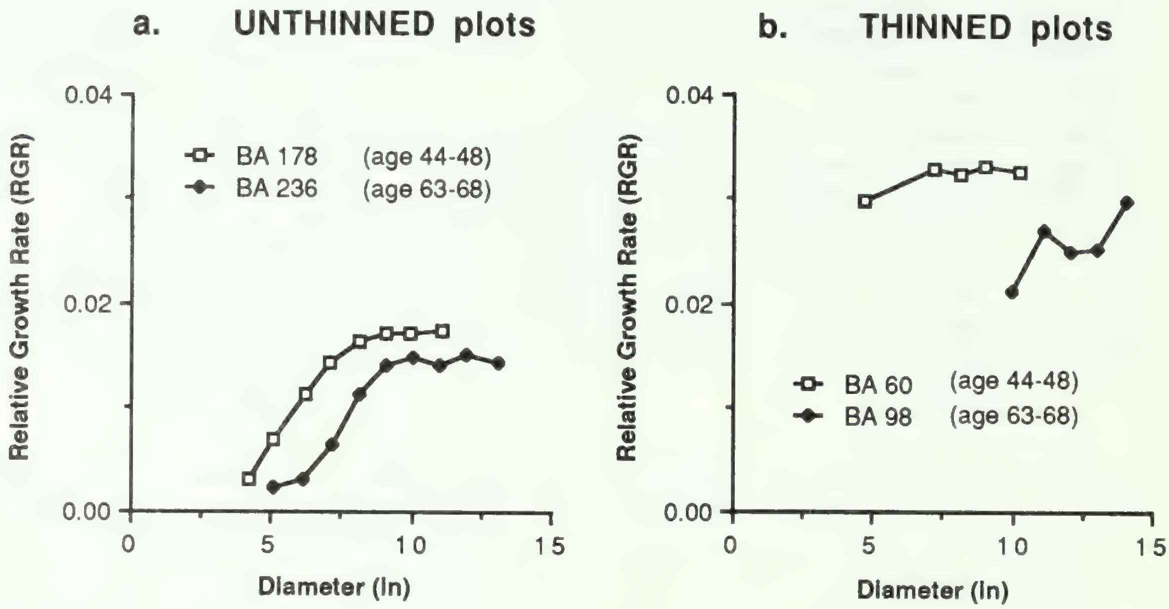

Figure 6. RGR for unthinned stands (entering self-thinning) and for thinned stands at ages 44-48 and 63-68.

However, during this same growth interval, the RGR dropped for the thinned stands as well (Figure 6b). The reduction in RGR that occurred at ages 63-68 even though stand density had been reduced to 60 square feet at ages 43 and 48 was apparently related to age and tree size because the stand had grown to only 98 square feet of basal area by age 62. These trees, relatively free to grow after thinning at age 43 and 48, declined in RGR the following 15 years. Thus, part of the drop in RGR for the unthinned plots as self-thinning developed can likely be attributed to increased tree age and size and not solely to competition.

These are only two of the many ways RGR can reveal what is happening within the stand.

BENEFITS OF RGR

RGR can readily be used to calculate the growth measures needed in the application process.

RGR is easy to calculate and easy to use.

RGR provides a measure of growth that adjusts for the size of the production base. It provides a relative comparison among trees of unequal size or stands of unequal basal area. It provides a ready description of trees or stands over time with automatic adjustments for the size of the production base.

Based on this evaluation, RGR appears to be a stable measure that is sensitive to thinning treatments. It shows promise for developing stand and tree models and for describing the within-stand dynamics.

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summer of 1980 an additional 7 installations became a part of the project. These installations are located in ten counties in Georgia, eight in Florida and one in South Carolina.

Each installation consists of a set of monumented plots which were established in 2- to 3-year-old mechanically site-prepared slash pine plantations after initial planting mortality had occurred. Individual plots at each installation represent planting survival densities of 100, 200, 300, 450 and 700 stems per acre (spa), as evenly spaced as possible. Two types of plots are contained in each installation: basic subseries (BS) plots which represent a range of planting survival densities and were to remain unthinned for the duration of the study, and suppression and release subseries (SAR) plots which were intended to represent the same initial stocking levels as the BS plots and to accommodate the thinning treatments.

Thinning was selective from below, aimed at uniform distribution of desirable remaining trees. Thinning intensities were determined by the surviving stems per acre of the BS plots of successively lower nominal stockings. For example, if there were three SAR plots with nominal stockings of 700 spa, one was thinned to the same number of stems per acre currently surviving in the 450 spa BS plot, another was thinned to match the currently surviving stems per acre in the 300 spa BS plot, and the third was thinned to match the currently surviving stems per acre in the 200 spa BS plot.

RESULTS AND DISCUSSION

The 30 installations were divided into three classes, based on the age at which each installation was thinned and initial measurements taken. The first Class (with 12 installations) was thinned and initially measured in 1978 at an average age of 15.5 years. The second class (with 11 installations) was also thinned and initially measured in 1978, but at an average age of 11.8 years. The third class (with 7 installations) was thinned and initially measured in 1980 at an average age of 13.6 years. The grouping by these three thinning age classes was maintained throughout the data analysis. The 146 BS and 203 SAR plots were remeasured on a 2-year cycle during the summers of 1980, 1982 and 1984.

AVERAGE DBH

Average dbh growth trends for all unthinned BS plots are summarized in Figure 1, showing the extent to with dbh growth is affected by different initial densities. At age 12, the expected average dbh ranges from 4.2 inches for an initial density of 700 stems per acre to an average of 5.7 inches for 100 stems per acre. By age 21 the average diameters are expected to increase to 6.6 and 9.9 inches respectively.

Commonly observed effects of selective thinning from below on average dbh and on subsequent dbh growth are illustrated in Figure 2 for SAR plots with an initial density of 700 stems per acre. These plots were thinned (at about age 12) at 3 different intensities to match the number of surviving stems per acre in unthinned BS plots that had initial densities of 450, 300, and 200 stems per acre. Figure 2 also shows the resultant average dbh development in these plots relative to unthinned plots with the same number of stems per acre. The difference in average dbh between thinned and unthinned plots with the same number of stems per acre is an indication of the effect of competition on average tree size at the time of thinning. From age 12 to 21 the increase in average dbh was approximately the same or slightly greater in the thinned plots compared to unthinned plots with the same number of stems per acre.

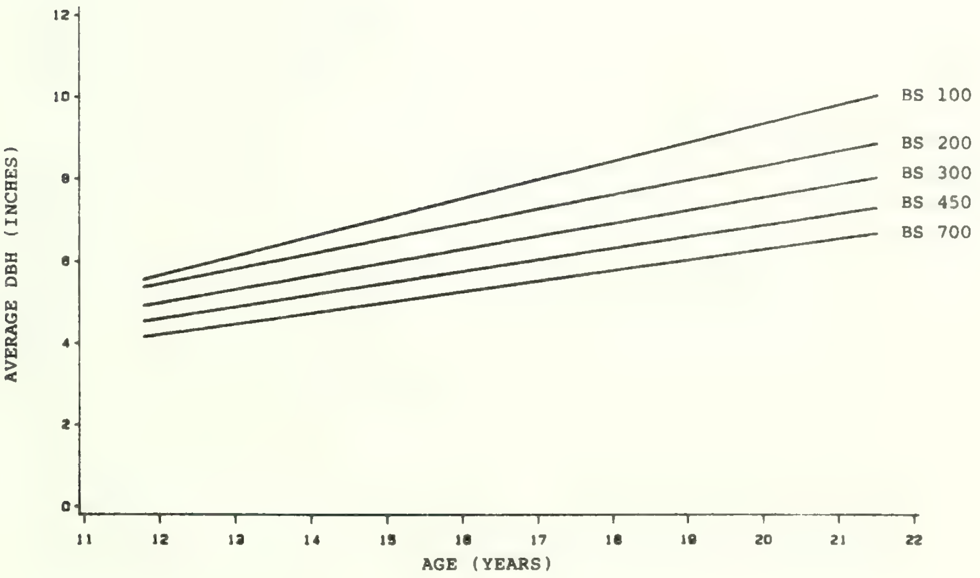

Figure 1. Average diameter at breast height (dbh) trends observed in unthinned site-prepared slash pine BS plots with different initial planting densities.

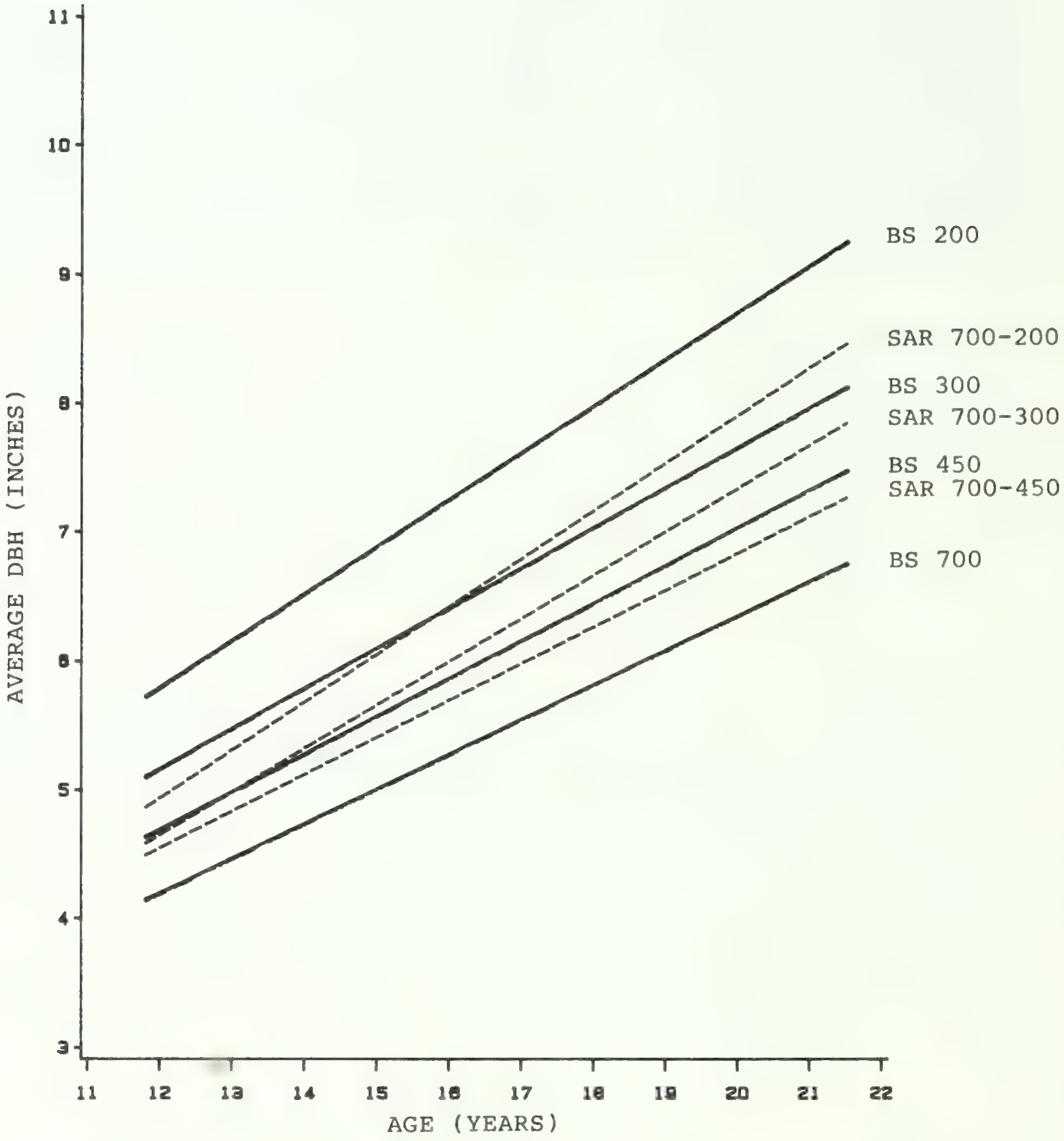

Figure 2. Average diameter at breast height (dbh) growth on unthinned site-prepared slash pine BS plots and comparable SAR plots thinned to the same number of surviving stems per acre.

BASAL AREA PER ACRE

The basal area growth for a subset of the unthinned BS plots from age 12 to 21 is shown in Figure 3. For the initial measurement and the 1984 remeasurement, differences between mean basal area per acre for the SAR and corresponding BS plots, paired by installation, are also shown in Figure 3. The most significant differences between basal area per acre for SAR and the corresponding BS plots occurred in plots with a high planting density combined with a high thinning intensity. Basal area growth from age 12 to 21 in thinned SAR plots differed only slightly from basal area growth in corresponding BS plots. Within the 700 stems per acre planting density, plots thinned 700-200 had a mean basal area growth of 29.1 sq. ft./acre. Plots thinned 700-300 had a mean of 44.2 sq. ft./acre and plots thinned 700-450 had a mean of 50.9 sq. ft./acre.

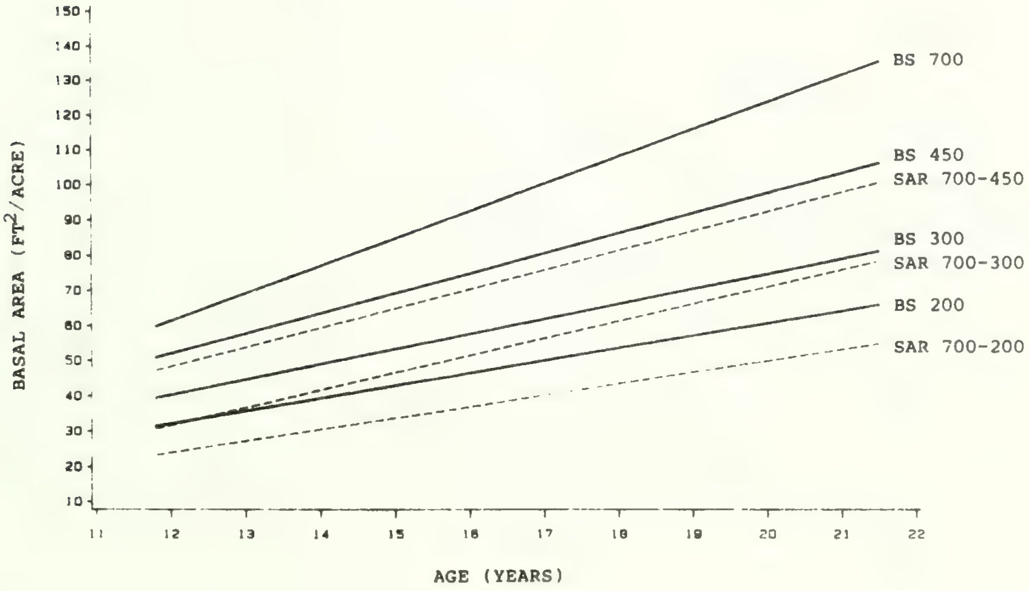

Figure 3. Average basal area per acre (sq. ft.) observed in unthinned BS and thinned SAR plots in site-prepared slash pine plantations.

TOTAL STAND VOLUME

Total stand volume, defined as total inside-bark cubic-foot volume, for unthinned BS plots increased with planting survival densities from 100 to 700 spa at all measurement ages is shown in Figure 4. The mean total volume for a planting density of 200 spa increased from 720 cu. ft./acre at age 12 to 1480 cu. ft./acre at age 21 for a net volume growth of 760 cu. ft./acre. For the 700 spa plots, the mean total volume increased from 410 cu. ft./acre at age 12 to 2725 cu. ft./acre at age 21 for a net growth of 2315 cu. ft./acre.

Observed differences between mean total volume for the SAR and corresponding BS plots, paired by installation, are also shown in Figure 4. For thinned stands within a given planting density, total volume growth is negatively correlated with the thinning intensity; plots thinned 700-450 had a net growth significantly greater than corresponding plots thinned 700-200.

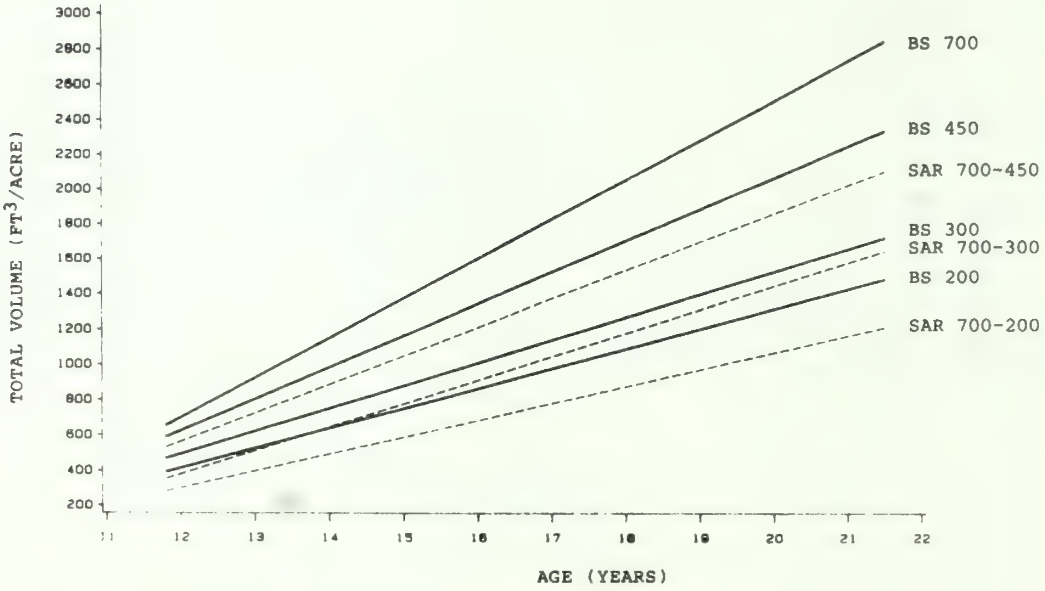

Figure 4. Total stand volume per acre (cu. ft.) observed in unthinned BS and thinned SAR plots in site-prepared slash pine plantations.

CONCLUSIONS

Control of density at stand establishment, and subsequently by thinning, is an important aspect of timber management. To properly evaluate the potential role of thinning requires a thorough understanding of the relationship between tree growth and growing space. Several firm conclusions concerning this relationship can be drawn from the statistical analysis of the data in this study. These are:

1) Stem diameter growth at breast height (dbh) is negatively correlated with stand density.

2) For thinned stands within a given planting density, dbh growth is positively correlated with the thinning intensity.

3) Stand basal area and total volume are positively correlated with stand density. For thinned stands within a given planting density, growth is negatively correlated with the thinning intensity.

In the comparison of unthinned plots and corresponding plots thinned to the same number of surviving stems per acre, the statistical analysis revealed very little significant difference among these plots in terms of average dbh, basal area and total volume growth. The only exceptions were in the comparison of unthinned plots planted at a low density and corresponding plots which were thinned from a much greater density. Specifically, this involved unthinned plots at the 200 density compared to plots thinned from 700 to the 200 density; in all cases, unthinned plots had larger basal are and volume values than did the corresponding thinned plots. Other cases, though not statistically significant, reveal that subsequent growth on heavily thinned plots seldom exceeded the growth on the corresponding unthinned plots.

The purpose of this study was to provide information on the growth response of trees in relation to planting density and thinning regime. The results may suggest possible management options but the ultimate choice must be made by the forest manager in conjunction with economic considerations and stand requirements.

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DEVELOPMENT OF A STAND DENSITY MANAGEMENT MODEL FOR PURE BLACK SPRUCE FOREST TYPES WITHIN CENTRAL NEWFOUNDLAND.

I. APPLICABILITY OF THE SELF-THINNING RULE.

Peter F. Newton[1]

ABSTRACT. The self-thinning rule describes the asymptotic total stem volume (V)-number of trees per unit area (N) relationship as inversely proportional with a power exponent of -0.5 within stands undergoing density-dependent mortality. The applicability of this relationship within black spruce (Picea mariana (Mill.) B.S.P.) stands during self-thinning was the subject of this study. Principal component analysis was used to estimate the parameters of the rule. Tests of hypotheses were employed to determine if V and N were significantly correlated and whether the slope of the observed V-N relationship was significantly different from the expected value. The data consisted of 37 growth periods derived from twenty-seven 0.081 ha semi-permanent sample plots situated on sites of medium quality throughout central insular Newfoundland. From these data 15 asymptotic growth periods were selected during which density-dependent mortality occurred. Results indicated that V and N were significantly correlated (r=-0.8404) and the slope of the observed V-N relationship (-0.60) did not significantly differ from the expected value (-0.5) at the 95% confidence level.

INTRODUCTION

In order to realize future wood fibre requirements forest managers within insular Newfoundland have undertaken an intensive black spruce (Picea mariana (Mill.) B.S.P.) silvicultural program employing density manipulation (plantation establishment and precommercial thinning) as the dominant forest improvement practice (Hayden 1986). However, due to the lack of a yield projection model forest managers are unable to predict future yields or evaluate their efforts. One possible solution is to develop a stand density management model for black spruce.

Stand density management models quantitatively describe the interrelationships between yield, density and mortality at various stages of stand development, e.g., Tadaki's (1963) stem volume-density diagram, Ando's (1968) stand density control diagram, Aiba's (1975) height-diameter-density-volume diagram, Drew and Flewelling's (1979) density management diagram and Kikuzawa's (1983) yield-density diagram. These models employ quantitative yield-density relationships derived from ecological studies concerning intraspecific competition: (i) the self-thinning rule (Yoda et al. 1963), (ii) the reciprocal equation of the competition-density or yield-density effect (Shinozaki and Kira 1956), and (iii) yield indices (Ando 1962, 1968).

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Through the implementation of such models the forest manager can predict future yields for various density conditions and manipulations, and thus determine if management objectives are to be realized under a given intensity of management.

Before this modeling approach for black spruce stands can be accepted, these conceptually based yield-density relationships must be evaluated. The initial objective of this study was to determine the applicability of the self-thinning rule within black spruce stands undergoing density-dependent mortality.

SELF-THINNING RULE

The self-thinning rule (Yoda et al. 1963) describes the asymptotic total aerial biomass-density relationship as inversely proportional with a power exponent of -0.5 within plant populations undergoing density-dependent mortality. Although the rule was originally derived empirically, Yoda et al. (1963) provided the following geometric derivation assuming that the geometry of plants remains constant during growth and population development, and self-thinning occurs only on fully occupied sites.

- (i) The mean above-ground biomass per surviving plant ($\bar{B}$) is directly proportional to the cube of some unspecified linear size dimension (l), $\bar{B} \propto l^3$.
- (ii) The mean ground area occupied by a plant (s) is directly proportional to the square of this linear dimension, $s \propto l^2$, and inversely proportional to density (N), $s \propto N^{-1}$.
- (iii) Thus combining the relationships in (i) and (ii), $s \propto l^2 \propto (l^3)^{2/3} \propto \bar{B}^{2/3} \propto N^{-1}$, and adding a constant results in the self-thinning rule.

$$\bar{B} = K1 \bullet N^{-3/2} \quad \text{or equivalently,} \quad B = K2 \bullet N^{-1/2} \qquad (1)$$

where K1 and K2 are constants, and B is the total above-ground biomass of surviving plants per unit area.

The following modified rule where weight is replaced by stem volume has been employed in stand density management models.

$$\bar{V} = K3 \bullet N^{-3/2} \quad \text{or equivalently,} \quad V = K4 \bullet N^{-1/2} \qquad (2)$$

where K3 and K4 are constants, $\bar{V}$ is the mean stem volume per surviving tree and V is the total stem volume of surviving trees per unit area.

The rule has been empirically confirmed in over one-hundred even-aged monospecific plant populations irrespective of age, locality, species or site quality differences (Gorham 1979; White 1980). However, a recent analysis the empirical evidence found that the rule's parameters were correlated with plant type, shade tolerance, locality and site quality, and thus concluded that the generality of the rule should be rejected (Weller 1987).

METHOD

Weller (1987) suggests three major analytical improvements that should be used when evaluating the self-thinning rule:

(i) total biomass or total stem volume of surviving plants per unit area should be related to density rather than the mean biomass or stem volume per surviving plant since the latter method is statistically invalid,

(ii) parameter estimates of the rule should be obtained through principal component analysis (PCA) due to the error structure of the data, and

(iii) statistical tests of hypotheses should be used to interpret the results.

Therefore the parameters of actual total stem volume-density relationship during self-thinning were determined by PCA and statistical tests of hypotheses were used to interpret the resultant relationship.

DATA BASE

The study area, Forest Section B28a-Grand Falls of the Boreal forest region, occupies the plateau of central northern insular Newfoundland (Rowe 1972). The data were derived from twenty-seven 0.081 ha semi-permanent sample plots located in natural pure black spruce stands undergoing density-dependent mortality. All plots were situated on sites of medium quality, i.e., site indices of 9 to 13 m at an index age of 50 years (Page 1968).

The plots were initially established in 1947 and 1948, and remeasured two to three times at 10 or 11 year intervals. The following data were collected at establishment and subsequent remeasurements: (i) a grouped diameter frequency distribution tally (2.5 cm diameter classes, minimum 1.5 cm) for all living trees by species, and (ii) diameter (+/-0.03 cm) and age at breast height, and total height (+/-0.31 m) measurements on approximately ten dominant and/or codominant trees. In addition, dead trees were marked and tallied by diameter class and species during the 1957-58 remeasurement and subsequent remeasurements.

Thirty-seven periodic growth periods where density-dependent mortality was occurring were selected from the 1957-58 to 1967-68 and 1967-68 to 1978 growth periods. Mid-point volumes and densities were computed for each period. Volumes were calculated using Warren and Meades' (1986) total volume equations in combination with a second degree polynomial total height-diameter regression function derived from the sample tree data ((ii) above).

DETERMINATION OF THE ACTUAL VOLUME-DENSITY RELATIONSHIP

To ensure that the selected stands were at an asymptotic total stem volume-density condition undergoing density-dependent mortality the following selection criteria were used:

(i) only the outer most stands from a log total stem volume-log density bivariate plot were considered to be at a asymptotic volume-density condition,

(ii) these outer most stands had to have a minimum periodic density-dependent mortality rate of 5% per decade, and

(iii) the diameter distribution of these abiotic stems that died during the growth period had to be positively skewed at the 90% confidence level.

The last requirement was derived from studies on stand structural changes within density-stressed populations (e.g., Ford 1975; Harper 1977; Mohler et al. 1978; Westoby 1984). That is, since the size frequency distribution within a density-stressed population is usually positively skewed and density stress results in the death of the smallest sized individuals, a positively skewed abiotic sized distribution would be generated.

Employing this selection procedure fifteen growth periods were selected. These periods were derived from stands with a mean age of 52 years at breast height (SD=7.3), mean density of 9479 stems/ha (SD=3671), mean volume of 186 cu m/ha (SD=44.6) and a mean periodic mortality rate of 12% per decade (SD=6.0). Using the mid-point V and N values of the selected growth periods parameter estimates for the unconstrained rule, equation (3), were obtained by PCA as described by Sokal and Rohlf (1981).

$$\log(V) = \log(K5) - b1 \bullet \log(N) \qquad (3)$$

where K5 is a constant, bl is the slope and log refers to natural logarithms.

COMPARATIVE ANALYSIS

In order to determine if V and N were uncorrelated the null hypothesis that the product-moment correlation coefficient (r) is equal to zero was tested against the alternative hypothesis that r is not equal to zero. To determine if the slope of the actual total stem volume-density relationship was equivalent to the expected value the null hypothesis that bl is equal to -0.5 was tested against the alternative hypothesis that bl is not equal -0.5. The tests were conducted at the 95% confidence level.

RESULTS

The actual total stem volume-density relationship is illustrated in Figure 1 with associated parameter estimates. The strength of the linear association between V and N as measured by the correlation coefficient (r=-0.8404) was significant at the 95% confidence level. The fitted slope of -0.60 with a 95% confidence interval of -0.39 to -0.86 was not significantly different from the expected slope of -0.5. Thus the null hypothesis, i.e., bl is not significantly different from -0.5, was not rejected.

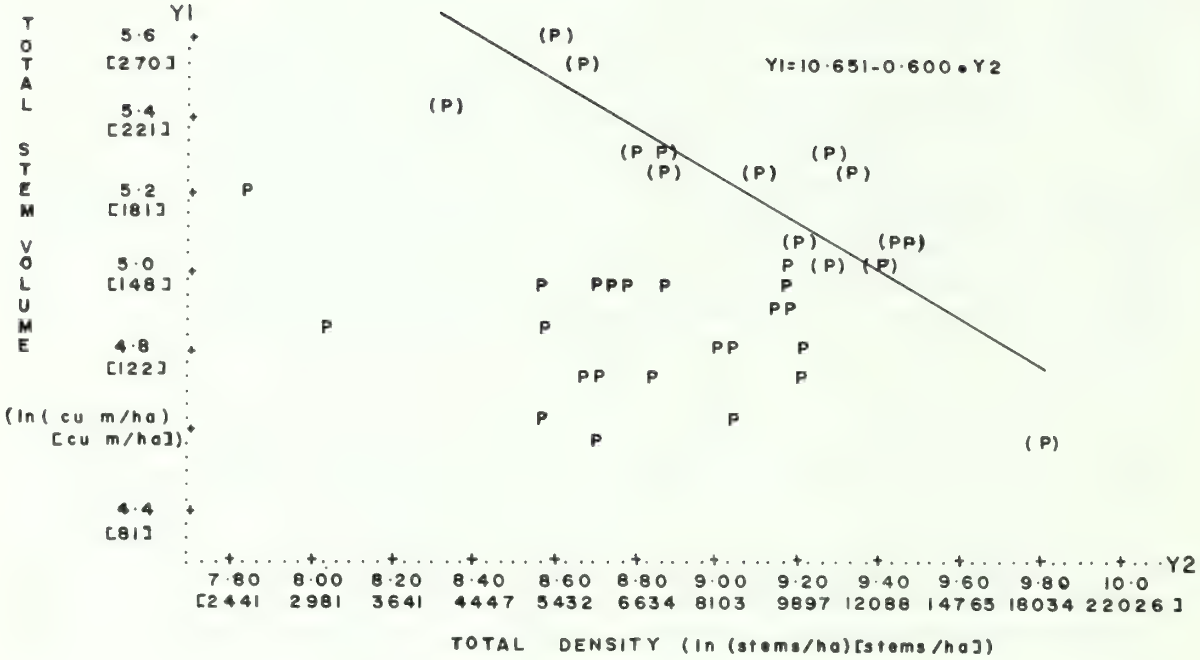

Figure 1. The asymptotic V-N fitted relationship (——) and associated data. (P)=asymptotic growth periods selected and used in fitting the V-N relationship. P=growth periods in which density-dependent mortality was occurring but not yet achieved an asymptotic V-N condition.

DISCUSSION

The results obtained in this study indicated that within black spruce stands undergoing density-dependent mortality the asymptotic relationship between total stem volume and density was linear on a logarithmic scale with a slope that did not differ from that predicted by the self-thinning rule. These results are similar to those reported by Weller (1987) when reevaluating Hatcher's (1963) data from black spruce stands in northern Quebec on a total biomass per unit area basis, i.e., B and N were significantly correlated and the slope of this relationship did not significantly differ from the expected value at the 95% confidence level. However, Wannamaker and Carleton (1983) reported a thinning slope of -3.75 for black spruce stands in northern Ontario, substantially different from the expected value. Wannamaker and Carleton (1983) attributed this departure to spatial pattern heterogeneity and the high shade tolerance of the species. However, the use of temporary sample plots, stand reconstruction methods, least squares methodology and mean rather than total values may have also been contributing factors.

The subjective selection of stands to be included in the fitting of the self-thinning rule reduces the objectivity of the analysis, however there is currently no general alternative (Weller 1987). The procedure employed in this study increases the objectivity of the selection method by only including stands at an asymptotic total stem volume-density condition in which density-dependent mortality occurred. However, this procedure does not eliminate subjectivity completely. Thus, until long-term permanent sample plot data become available for which the total stem volume-density relationships can be analyzed during extensive periods of self-thinning, the empirical evaluation of the self-thinning rule will be incomplete. Although the scope of this study was restricted to determining the applicability of the self-thinning rule within black spruce stands on an empirical basis, further study is required to evaluate the underlying assumptions employed in the rule's derivation. Recently these assumptions have being found to be untenable (Ziede 1987).

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RACIAL VARIATION IN SELF-THINNING TRAJECTORIES IN LOBLOLLY PINE

R. C. Schmidtling[1]

ABSTRACT. Data from a loblolly pine Southwide seed source planting in Georgia were analyzed to determine the effects of seed source on slope and level of self-thinning trajectories.

The graph of Ln(mean D^2H) versus Ln(number trees/plot) indicated that most of the planting had reached the self-thinning phase of development. The slope of self-thinning trajectories was slightly steeper than -3/2. Levels, or intercepts, varied significantly among provenances. The variation in carrying capacity by provenance was positively correlated to both site index and dominant-codominant height at age 30.

INTRODUCTION

Forest trees generally respond to crowding by reduced growth. As competition becomes more intense, the smaller, suppressed individuals die. The relationship between average tree size and number of trees in a given area that are undergoing self-thinning is often described by the -3/2 power rule (Yoda et al., 1963), where the line

$$\text{Log } \overline{V} = \log \beta_0 - \beta_1 \log N$$

describes an upper limit for the average volume of a tree, $\overline{V}$, at a given number of trees per area, N (Figure 1). The slope parameter, β_1, seems to be fixed at -1.5 regardless of site, age, or species (Yoda, et al., 1963; White and Harper, 1970; Harper, 1977; Gorham, 1979). According to White and Harper (1970), the intercept parameter β_0 varies with species but only within narrow logarithmic limits.

The importance of the natural self-thinning phenomenon in stand density management for practicing foresters has long been recognized (Reineke 1933). In the past few years, the -3/2 rule has been suggested as a basic model for stand density manipulation (Drew and Flewelling 1979). Recently, however, the universality of the -3/2 power rule has been seriously questioned (Weller, 1987; Carleton and Wannamaker, 1987; Zeide, 1987).

The -3/2 power rule has important implications for forest tree breeders (Nance et al., 1987). If the intercept parameter, β_0, as well as the slope, β_1, is fixed for a given species on a given site, then tree

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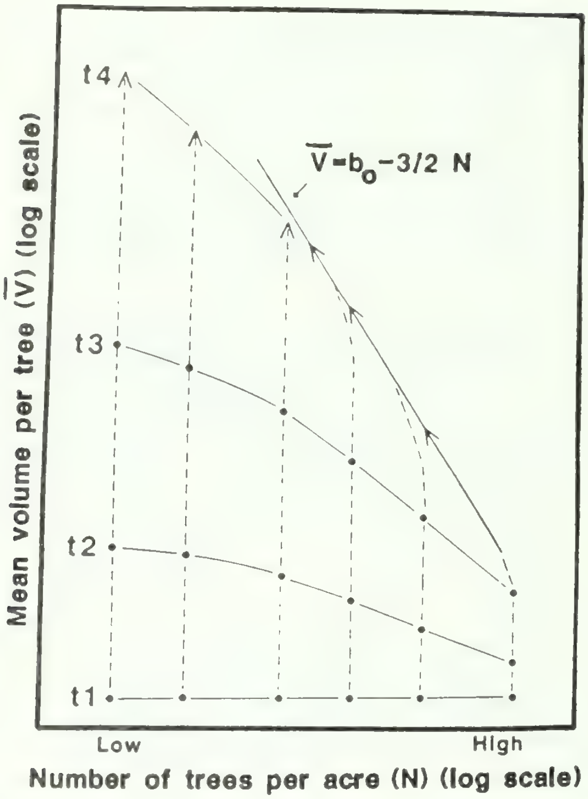

Figure 1. Relationship between mean volume per tree and stand density (adapted from Nance et al., 1987). Successive time periods are represented by solid lines labeled t1 through t4. The vertical dashed lines represent the progress over time for each of six stands planted at different densities. The arrow shows the final density size attained by the stands.

improvement is limited only to reducing the time interval that a stand of improved trees reaches the self-thinning limit and develops according to the self-thinning line. If, on the other hand, either the intercept or the slope can be manipulated genetically, then carrying capacity can also be influenced. Buford and Burkhart (1985) have found some evidence for genetic variation in carrying capacity.

The present study does not attempt to test the validity of the -3/2 power law, but rather seeks to determine the effects of genetic variation on the slope and intercept of self-thinning trajectories.

MATERIALS AND METHODS

Large-plot, long-term genetic studies for testing variation in self-thinning behavior are relatively rare. The Southwide Southern Pine Seed Source Study (Wells and Wakeley, 1966) provides one of the best opportunities for this type of testing. Although most of the plantings were thinned at age 15, many appear to have reached the self-thinning phase at age 30. Data from one of these plantings, in Dooly County, Georgia, was used for this study.

The planting was established in 1952-53 with planting stock from nine provenances (Table 1). A randomized complete-block design with four replications was used for the planting. Each replication of each provenance consists of a square, 121-tree plot, with 72 trees in border rows and 49 periodically remeasured interior trees. Spacing is 6- by 6-feet. Complete details of the Southwide study can be found in Wells and Wakeley (1966). Measurements of height and stem diameter at 4.5 feet (d.b.h.) at ages 10, 15, 20, 25, and 30 years were used for the present analysis. Log-log plots of number of trees per plot and volume index (d.b.h.^{2} X height) were used to examine self-thinning trajectories.

Density/volume intercepts and slopes were determined using the 25- and 30-year coordinates. Regression and covariance methods of Neter and Wasserman (1974) were used to test provenance differences in slope and intercept.

TABLE 1. Location of seed sources and parameters of self-thinning trajectories computed from 25 and 30 year data (Log-log scale).

Provenance		Self-thinning trajectory		Dominant height (ft)
Region	County	Slope	Intercept	
Eastern Maryland	Somerset	-1.69	8.33	66.1
Southeastern North Carolina	Onslow	-1.72	8.32	66.5
Eastern North Carolina	Pamlico	-1.51	7.74	66.4
Southwestern Georgia	Wilcox and Crisp	-1.59	7.95	65.1
Northern Alabama	Cullman	-1.87	8.72	61.1
Northern Alabama	Jefferson	-1.65	7.94	62.1
Southeastern Louisiana	Livingston	-1.78	8.67	67.0
East Texas	Angelina	-1.57	7.96	63.1
Southwestern Arkansas	Clark	-1.47	7.45	61.3
Mean		-1.61	8.00	64.3

Differences in slope were tested by comparing the full model:

$$Y_i = \beta_o + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \beta_4 X_{i4} + \beta_5 X_{i5} + \beta_6 X_{i6} + \beta_7 X_{i7} +$$

$$\beta_8 X_{i8} + \beta_9 X_{i9} + \beta_{12} X_{i1} X_{i2} + \beta_{13} X_{i1} X_{i3} + \beta_{14} X_{i1} X_{i4} + \beta_{15} X_{i1} X_{i5} +$$

$$\beta_{16} X_{i1} X_{i6} + \beta_{17} X_{i1} X_{i7} + \beta_{18} X_{i1} X_{i8} + \beta_{19} X_{i1} X_{i9} + \varepsilon_i$$

where

β's = model parameters

$Y_i = \ln(\overline{V}_1)$

$X_{i1} = \ln(N_1)$

$$X_{i2} = \begin{cases} 1 \text{ if observation } i \text{ from provenance } 2 \\ 0 \text{ otherwise} \end{cases}$$

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$$X_{i9} = \begin{cases} 1 \text{ if observation } i \text{ from provenance } 9 \\ 0 \text{ otherwise} \end{cases}$$

ε_i = residual error

with the reduced model not containing the interaction terms for slope:

$$Y_i = \beta_o + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \beta_4 X_{i4} + \beta_5 X_{i5} + \beta_6 X_{i6} + \beta_7 X_{i7} +$$

$$\beta_8 X_{i8} + \beta_9 X_{i9} + \varepsilon_i$$

by a straight-forward F test of the reduction in error sums of squares of the complete versus the reduced model.

Similarly, overall provenance differences in intercept were tested by comparing the above model with the model further reduced by eliminating the provenance variables:

$$Y_i = \beta_o + \beta_1 X_{i1} + \varepsilon_i$$

Statistical tests were made at the 0.05 level of probability.

RESULTS AND DISCUSSION

The volume/density plots indicate that self-thinning was occurring between ages 25 and 30 on nearly all the plots (Figure 2). Two plots, the Georgia plot in Block 2 and the North Carolina plot in Block 3, were exceptions out of a total of 36 plots, in that no mortality occurred between ages 25 and 30 years. On both plots, however, survival at age 25 was much less than average. These two plots were not used in computing slopes. The slopes averaged somewhat steeper than the expected -1.5, ranging from -1.47 for the Arkansas source to -1.87 for one of the Alabama sources (Table 1). The slopes averaged -1.61 and did not differ significantly from each other by provenance at the 0.05 level of significance ($F_{8,50} = 0.108$). Although slopes slightly steeper than -1.5 are in agreement with Zeide's (1987) conclusions, they are not inconsistent with the concept of an asymptotic limiting trajectory of -1.5; some of these plots may not have reached this limit at 25 years (Figure 3).

It is apparent in Figure 3 that the mean slopes by provenance for the 25- to 30-year data do not differ much from each other, nor are they greatly different from -3/2. Although the 30-year volume/density coordinates may not be on the -3/2 power line, it does not appear that they are asymptotically approaching the same line, i.e., the provenances appear to be headed for different intercepts. If they were approaching the same intercept, one would expect the slopes closer to the origin to be steeper. Although this appears to be true with one of the Alabama sources, it is not true overall. In fact, there is a slight tendency for the slopes to be steeper as one moves farther from the origin. The correlation of slope with intercept is (r = 0.345, 32 d.f.).

The provenances differed significantly at the intercept ($F_{8,58} = 7.07$). The intercepts range from 7.45 for the Clark County, Arkansas, source to 8.67 for the Livingston Parish, Louisiana, source. The intercepts are correlated with 30-year dominant height (r = 0.65, 34 d.f.). Thus there seems to be some evidence for genetic variation in carrying capacity.

CONCLUSIONS

Forest tree breeders can take some comfort from the data presented here. Although certainly not conclusive, the results suggest that genetic improvement can be made in final yield or carrying capacity, as well as increasing early growth, and that this yield/density limit appears to be positively correlated with height growth, the trait most often used as a basis for genetic evaluation.

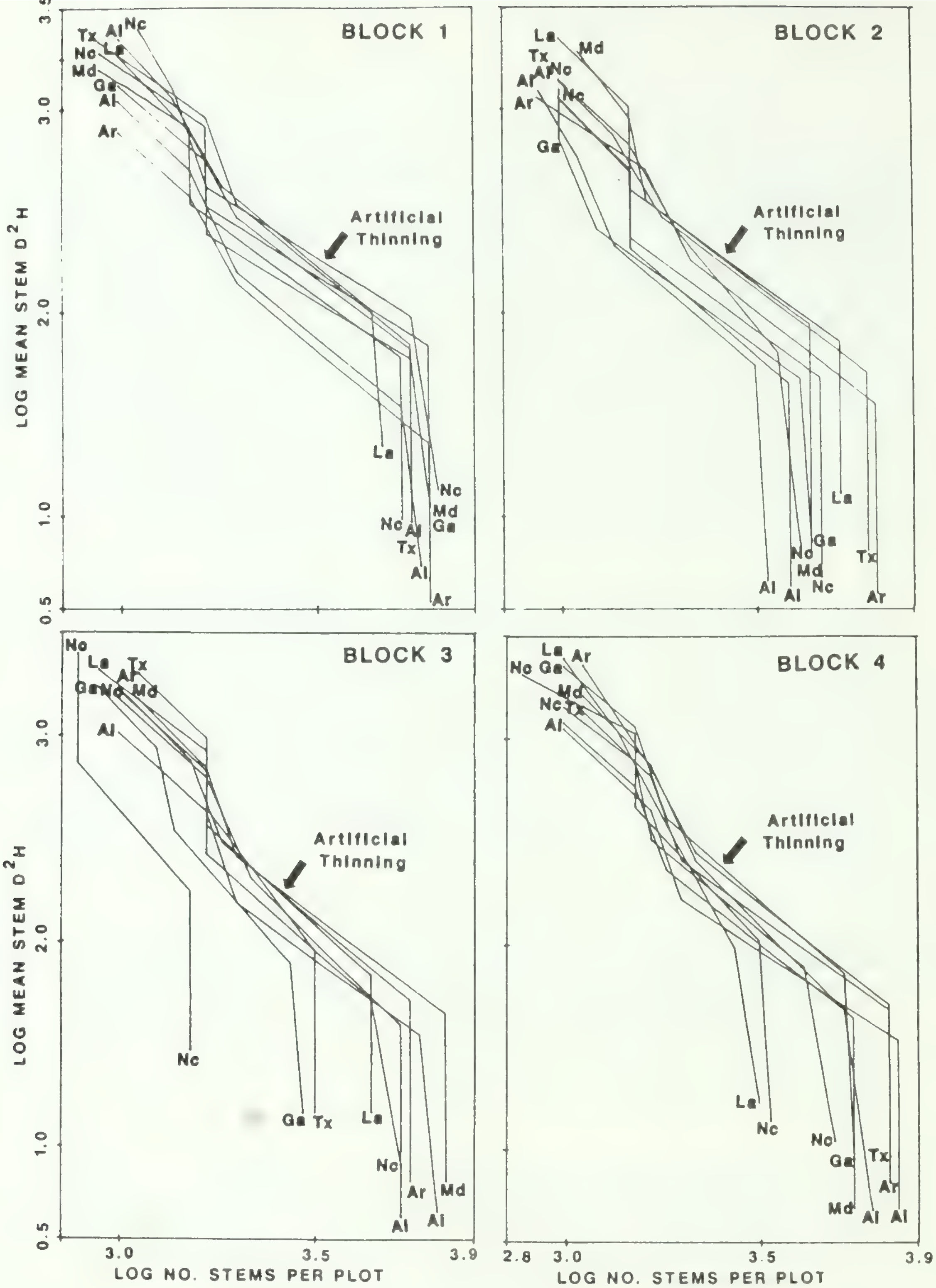

Figure 2. Size/density (self-thinning) trajectories for nine loblolly pine provenances planted in Dooly County, Georgia. Based on data from 10, 15, 20, 25, and 30 years. Artificial thinning refers to a thinning at age 15, which was mainly a mechanical thinning. Abbreviations (La, Ar, etc.) refer to the State from which the source originated.

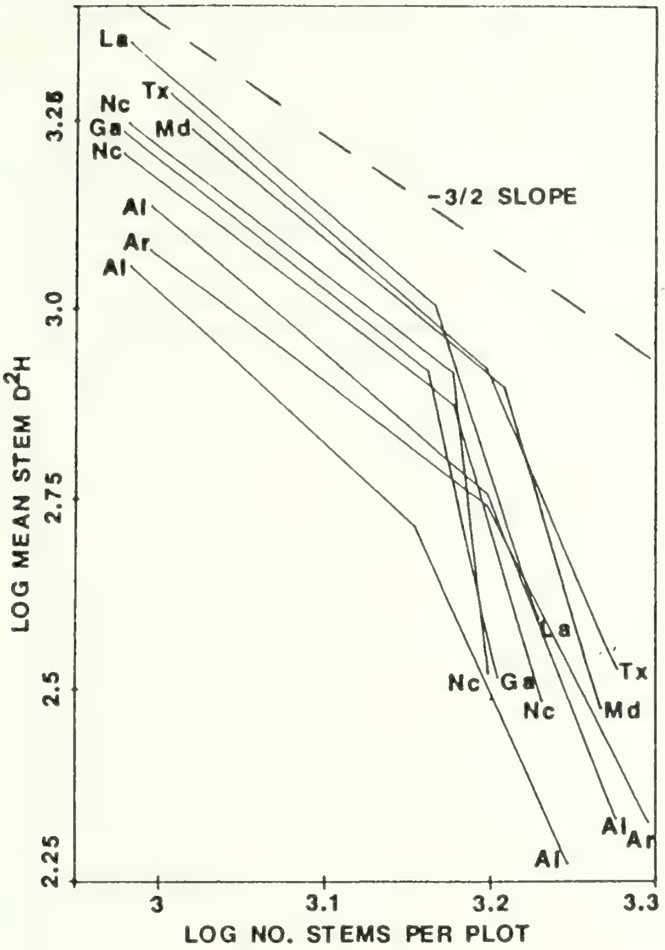

Figure 3. Size/density (self-thinning) trajectories for nine loblolly pine provenances planted in Georgia. Means of four replications (from Figure 2). Trajectories are based on 20-, 25-, and 30-year data. Abbreviations are the same as for Ffigure 2.

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AUTOCORRELATION AND COMPETITION IN EVEN-AGED STANDS OF DOUGLAS-FIR IN THE NETHERLANDS

H. Schoonderwoerd and G.M.J. Mohren [1)]

ABSTRACT. Spatial pattern in even-aged stands of Douglas-fir was analyzed using spatial autocorrelation methods. The stands were selected from a large data-base containing permanent field plots in which the position of the individual trees was known from the time of first measurement. The stands were repeatedly thinned, and measured over periods of up to 60 years. The correlation between neighbour trees indicated that competition may play a major role in determining the spatial pattern of homogeneous stands. The occurrence of negative correlations as a result of competition, however, depends on site quality and soil homogeneity, in combination with the applied thinning regime.

INTRODUCTION

The spatial distribution of trees in a forest stand determines, together with the dimensions of the tree crowns, the degree of canopy closure and the extent to which resources available for growth are utilized by the stand. The distribution of the available resources (light, water and nutrients) over the trees is an expression of the competition regime in the stand. Thinning management, either non-selective in case of mere density regulation or selective, when future crop trees are released to optimize economic yield, deliberately tries to modify these competitive interferences by changing stand density and the spatial pattern of the trees. The spatial distribution of individual trees is the result of stand dynamics and stand management in the past; it sets the boundaries for future stand development, and determines future thinning options.

Several aspects of even-aged stand development and management may cause typical spatial patterns in even-aged stands to deviate from randomness. Competition between neighbouring trees will

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result in small trees standing next to larger ones and vice versa, with the strongest competitors regularly sparsed over the stand area (Stern, 1966). The same holds to some extent for thinning operations: thinning usually leads to a regular distribution by aiming at an equal distribution of the available resources over the crop trees in the stand and at the same time maintaining canopy closure in order to maximize yield. Soil heterogeneity on the other hand, will lead to grouping or clustering of larger, more vigorously growing trees on favourable microsites, and groups of smaller trees on less favourable microsites. In addition to this, a number of other factors can influence the variability of tree-size in the field, notably genetic variations in relative growth rate (Benjamin and Hardwick, 1986).

The mechanisms mentioned above may cause the spatial pattern of a stand to vary from completely random (e.g. due to genetic variation), to regular (caused by competition), and to clustered (e.g. as a result of soil heterogeneity). Knowledge of these aspects of spatial pattern is required to study competition. The analysis here, is confined to repeatedly thinned even-aged stands of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) in the Netherlands. Our research concentrates around a correlation analysis of individual tree diameters within these stands, and on its development over time. The results provide a rationale for understanding of the general structure in forest stands. This allows simulation of spatial pattern and incorporation of individual tree aspects in whole-stand models, without taking into account the actual positions of the trees in the field (Reed and Burkhart, 1985; van Gerwen et al., 1987).

METHODS OF STUDYING SPATIAL PATTERN AND COMPETITION

Competition is one of the driving forces resulting in differences in tree size in otherwise homogeneous stands. As such, it has been studied extensively with the purpose of incorporating mutual interference between trees in tree and stand modelling, either with the aim of constructing distance-dependent individual tree models, or in order to account for variability between trees in distance-independent models.

In most distance-dependent individual tree models, the approach focuses on the quantification of competition levels for individual trees by assuming some zone of influence for each tree (see reviews by Ottorini, 1978, and Gates and Westcott, 1978). From data on the spatial pattern of the stand, competition indices for each tree can be calculated, and after a correlation analysis has established the relationship between the growth of an individual and its competitive status, the competition index can be incorporated in a growth model (e.g. Faber, 1983). This approach thus determines the instantaneous effect of competition, inferred from the spatial pattern, on tree growth.

An alternative approach to the relation between spatial pattern and competition is to look upon the spatial pattern of a stand as the result of several long-term processes, competition being one of them. First, spatial pattern is described using some stand-level index, and its development over time is calculated from permanent plot data. Next, the observed trends in spatial pattern are compared with hypothetical trends that are formulated from assumptions on the growth of individual trees as determined by the degree of stand heterogeneity and competition. The comparison allows for testing of the underlying assumptions regarding the importance of competition in determining differences in tree growth within the stand.

In this paper, spatial autocorrelation of tree dbh, expressed as the correlation between the diameter-at-breast-height of a subject tree and the diameter of its neighbours, is used to describe the spatial pattern during the development of even-aged stands of Douglas fir. With regard to competition, this means that emphasis is on nearest-neighbour competition, as compared to diffuse competition where plants of a certain size are compared to plants of average size for the stand.

As a stand-level index of spatial autocorrelation we use Cliff and Ord's (1973) extension of an index presented by Moran (1950):

$$I = \frac{n \sum_i \sum_j w_{ij} (x_i - \bar{x}) (x_j - \bar{x})}{W \sum_i (x_i - \bar{x})^2}$$

where n is number of trees, x_i is dbh (cm) of subject tree i, $\bar{x}$ is mean dbh (cm), x_j is dbh (cm) of neighbour tree j, w_{ij} is weight of interaction between tree i and its neighbour j, and W is weights summed over all interactions.

Moran's I is asymptotically normally distributed (Cliff and Ord, 1973; Reed and Burkhart, 1985) with:

$$E(I) = -1/(n-1)$$

$$E(I^2) = \frac{n((n^2-3n+3)S_1-nS_2+3W^2)-b_2((n^2-n)S_1-2nS_2+6W^2)}{(n-1)(n-2)(n-3)\,W^2}$$

$$S_1 = 1/2 \sum_i \sum_j (w_{ij} + w_{ji})^2$$

$$S_2 = \sum_i (\sum_j w_{ij} + \sum_j w_{ji})^2$$

$$b_2 = m_4/(m_2)^2$$

(m_k is k-th sample moment about the sample mean)

These formulas have been employed to calculate standardized values of I (I_s), which can be tested using critical values from the standard normal distribution. Here, trees are considered to be neighbours of a subject tree i, if their distances from i are less than a preset limit R. Correlation indices have been calculated for R equal to 2m, 4m, 6m and 10m.

FORMULATION OF AN ELEMENTARY MODEL

With regard to competition, the life cycle of even-aged plantation forests can be divided into three development stages. The first stage comprises the time after planting until the onset of competition, which occurs at the time of canopy closure. During this stage of development there is no interference between individual trees, the allocation of resources for growth to an individual tree is not influenced by its neighbours, and the trees grow at their maximum growth rate for that particular site. On homogeneous sites variation in growth rates is genetically controlled and essentially random. A clustered distribution of tree sizes may occur due to soil heterogeneity or as a result of local occurrence of fungal or insect attacks. As a result, during this stage no significant neighbour correlations are expected for stands on homogeneous sites, free from diseases and pests, and positive correlations may occur on heterogeneous sites.

The second stage of stand development starts off with the random tree size distribution resulting from the stand's development prior to canopy closure. Allocation of growth resources to an individual tree is now increasingly modified by its neighbouring trees and variation in tree growth rates is partially governed by competition. As growth proceeds, competition intensifies and its influence on the variation in tree sizes increases. These interactions between trees will lead to a pattern of evenly dispersed large trees neighbouring small trees. In this stage, genetically induced variation in growth rates relates to differences in competitive ability as opposed to the development prior to canopy closure, during which genetic differences in site capturing ability are most important. The different mechanisms lead to poor juvenile-mature correlations of tree growth (Cannell, 1984). When nearest neighbour competition is the overriding factor, the stand development after canopy closure is expected to lead to negative spatial autocorrelation. This trend will be delayed (or masked altogether) when genetic variation is large. Soil heterogeneity again may result in positive correlation.

As the stand ages and height growth slows down, a third stage of stand development occurs, in which relatively free growing mature trees are evenly distributed over the area. At this stage, competition between trees becomes less pronounced. On homogeneous sites, and in absence of large genetic variation, tree size will show little variation, mainly caused by the accumulation of random defects in the canopy. Thus, the negative correlation resulting from competition in the second stage can be expected to become less in older stands.

ANALYSIS OF THE SPATIAL PATTERNS OF THE SELECTED FIELD PLOTS

This model can be evaluated by calculating spatial autocorrelation indices during stand development, using permanent field plots of even-aged stands. Here, three plots have been selected from a large data-base on Douglas-fir growth in the Netherlands. This data-base, that includes the field coordinates of individual tree locations, consists of permanent field plots which have been established as provenance trials (de Vries 1961) and thinning experiments (Becking and van Laar 1958). The plots have been measured at 3 to 5 year intervals and in most cases a thinning has been carried out at the time of measurement. Diameter-at-breast-height (dbh) has been measured for each tree in the plot, and all trees removed by thinning have been recorded. A thinning criterium has been used, implying that the ratio of average tree distance and dominant height is held constant throughout stand development. With this approach, using what is known as Hart's S percentage (Ottorini, 1978), different thinning intensities were defined. The stands are thinned from below, with the aim of releasing future crop trees by removing smaller competitors, while keeping the canopy closed.

For neighbour zones R = 2m, 4m, 6m, and 10m, standardized values I_s are calculated for the plots Gieten 5 (Fig. 1a), Esbeek 23 (Fig. 1b), and Nieuw Soerel 2 (Fig. 1c). Gieten 5 is a plot on a good quality site, and the plot is moderately thinned according to a value for S % equal to 19. Esbeek 23 is a medium site quality plot, lightly thinned to maintain S % = 16. Nieuw Soerel 2 is also on a medium quality site, but with a thinning level that maintained S % = 21.

For plot Gieten 5 (Fig. 1a), trends in spatial correlation are in close agreement with the formulated model. Significant negative correlations between the dbh of a subject tree and the dbh of its neighbours are observed around age 30 for neighbours located less than 4 m from a subject tree. This clearly demonstrates that competition is an important factor in stand development. Thinning at age 24 left the stand with very few trees located at less than 2m from each other and the correlations for R = 2m are trivial. Stand spatial pattern at age 44 shows clear negative correlation for R = 6m, although significance is less as compared to age 30. Correlations for R = 10 m do not significantly differ from zero.

Prior to its first thinning, plot Esbeek 23 (Fig. 1b) shows a significant negative correlation at age 21 for R = 2m, again demonstrating that nearest neighbour competition occurs. As opposed to plot Gieten 5, however, none of the correlations for the stand after the first thinning differs significantly from zero. Even though thinning intensity for this plot is low (S % = 16), the periodic thinning regime prevents distinct spatial patterns to develop between age 21 and age 40.

Plot Nieuw Soerel 2 (Fig. 1c) is also on a medium quality site, but experienced higher thinning intensity (S % = 21). Significantly negative correlations are not observed during the measurement interval. The generally high positive correlations for R equal to 2m are due to the fact that the few trees left in the stand that are closer to each other than 2m, are almost all small trees that have been ignored in subsequent thinnings.

Weighting of the contribution of the neighbouring trees according to the reciprocal values of the distance to the subject tree

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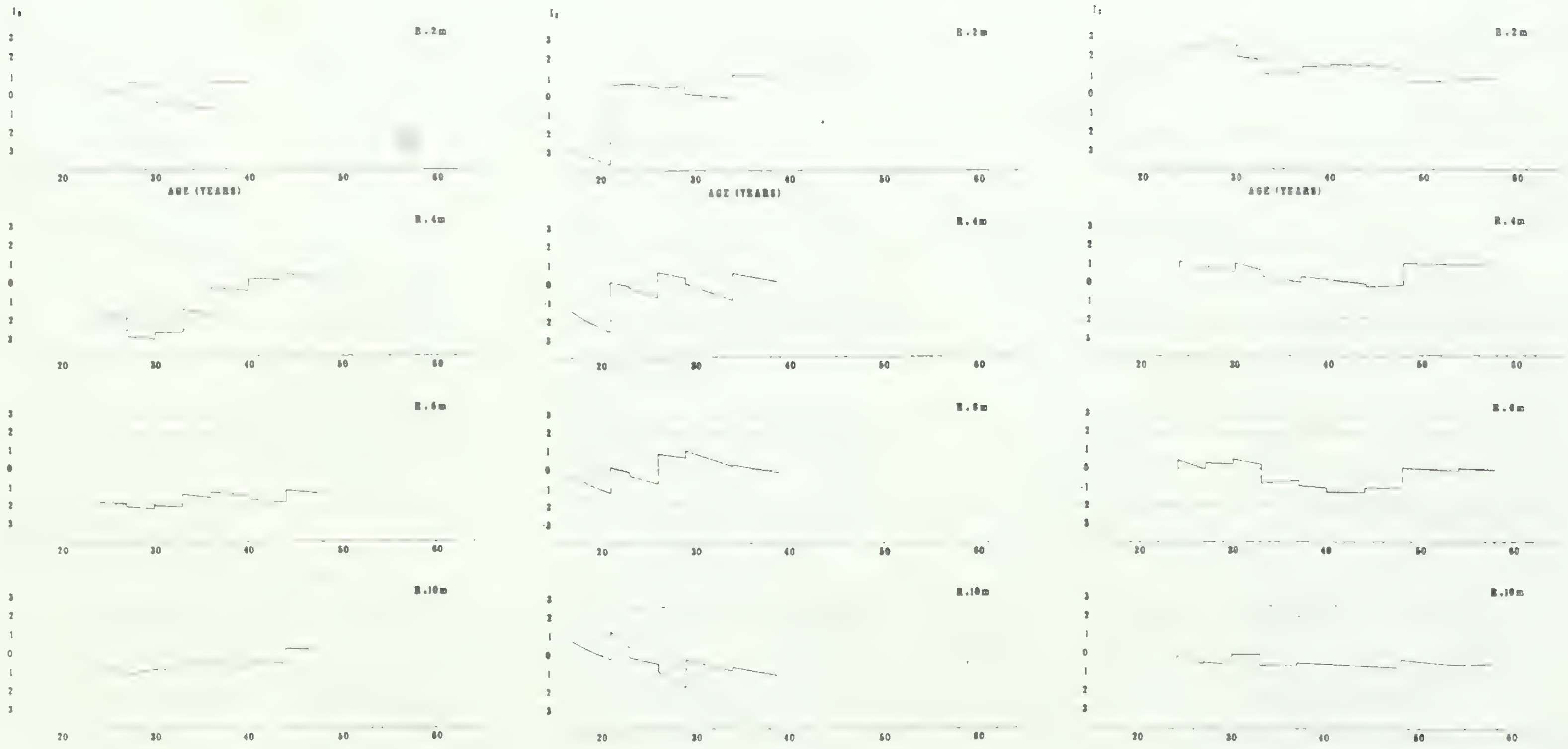
Figure 1. Spatial autocorrelations during stand development for three selected field plots Gieten 5 (a), Esbeek 23 (b), and Nieuw Soerel 2 (c). Selection radii (R): 2m, 4m, 6m and 10m. Outer dashed lines: 0.5 % critical value of standard normal distribution; Inner dashed lines: 2.5 % critical values.



(a) (b) (c)

(using $w_{ij} = L_{ij}^{-1}$, and $w_{ij} = L_{ij}^{-2}$, where L_{ij} is the distance between trees i and j) did not add substantial information and hence is further ignored here. The effect of weighting the interactions with the reciprocal of distance or squared distance for a given R appeared to be equivalent to the selection of neighbours for smaller values of R.

DISCUSSION AND CONCLUSIONS

The negative correlations observed in the plots Gieten 5 and Esbeek 23 clearly show the importance of competition in stand development leading to typical spatial patterns of evenly distributed large trees neighbouring small trees. Whether these patterns actually develop in the life cycle of a stand, depends on the combination of applied thinning regime and site quality. Thinnings from below concentrate on removing the smaller trees from the stand. This means that thinning is merely preceding mortality and the spatial pattern resulting from competition will be neutralized. While growth proceeds negative correlations on a larger scale will develop, which will again be neutralized by thinning from below. This cycle will be repeated until the stand reaches the stage of old-stand development and competition effects have lost their importance in stand development. The time between two successive cycles depends on the growth rates of the trees as determined by the quality of the site. Periodic thinnings with a considerably shorter cycle will prevent negative spatial autocorrelation to occur, as in the case of the plots Nieuw Soerel 2 and Esbeek 23.

Other analysis of spatial pattern along the same lines as described here had varying results, showing strong negative (Stern, 1966) as well as positive correlations (Reed and Burkhart, 1985). Our analysis shows that stand age and developmental stage should be considered in relation to spatial autocorrelation indices in order to evaluate effects of competition and soil heterogeneity. Large genetic heterogeneity, when present in the stand, may mask any effects of competition for space, a complication that is avoided here by investigating pure stands used in provenance research.

The spatial pattern at the time of canopy closure is the initial condition for the second stage of stand development where competition is a major mechanism influencing differences in individual tree growth. Small differences in size and local density in the seedling stage can be magnified during the exponential growth period prior to canopy closure, when competition is absent (Spitters, 1988). In that case the resulting clustering of trees at the time of canopy closure may limit the development of negative correlations, and the effects of competition cannot be singled out clearly. The stands used here were planted in a regular pattern, and it can be assumed that the occurrance of canopy closure has been fairly regular throughout the stand.

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SELF-THINNING IN SITKA SPRUCE (*PICEA SITCHENSIS* (BONG.) CARR.) STANDS IN DENMARK. PRELIMINARY RESULTS.

J. P. Skovsgaard [1]

ABSTRACT. Unthinned Sitka spruce stands in Denmark do not obey the self-thinning rule ($V = kN^{-1/2}$). The exponent is found to be approx. -0.95 - -1.00 rather than -0.5. The diameter distribution develops a marked bimodality with D_g consistently located in the depression between the 2 modes. Shortly after canopy closure the volume distribution achieves final structure with respect to D_g: from that time, total stemwood with DBH > D_g amounts to approx. 73% of stand volume. On this basis, it is possible for the forest district officer to make early predictions of end-use volume.

BACKGROUND

In Denmark, Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is a commonly used alternative to the Norway spruce (*P. abies* (L.) Karst.), e.g. at the coast-near dune areas, on clayey soils and on soils with a high ground water table. The aimed at thinning regime is usually in youth heavy, later very light thinning. This is to maximize economic yield (fast diameter development, short rotation) and to reduce the hazard of windthrow. However, unfavourable economic return of the first thinnings in coniferous crops has brought up the question, whether it is possible to produce the desired end-product with a no-thinning regime. Anyhow, a no-thinning regime has the advantage of reducing the hazard of windthrow to an absolute minimum.

The possibilities depend to a high degree on the biology of the species. Sitka spruce shows, as compared to the Norway spruce, a better natural ability to differentiate, at least in unthinned stands (Henriksen 1958). Further, the volume production is 10-50% higher than that of the Norway spruce. This implies that, when left unthinned, Sitka spruce has the potential of producing timber dimensions, even within a reasonable space of time.

This is the background of the research-project "A No-thinning Regime in Sitka spruce". Some preliminary results are presented here.

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INTRODUCTION

THE SELF-THINNING RULE

The self-thinning rule describes reciprocal changes in plant biomass and number of plants due to competition during the development of even-aged monocultures. The original formulation of the rule (Yoda et al. 1963) is:

$$w = kN^{-3/2} \tag{1}$$

where w is the average plant mass, N is the number of plants and k is a species specific constant,
or, alternatively:

$$W = kN^{-1/2} \tag{2}$$

where W is the stand biomass, etc.

Another equivalent formulation has been put forward (Long & Smith 1984):

$$D_g = kN^{-0.625} \tag{3}$$

where D_g is the diameter corresponding to mean basal area of stand.

A logarithmic transformation defines the self-thinning line, e.g.

$$\log W = \log k - 1/2 \log N \tag{4}$$

This line is regarded as a sort of dynamic upper equilibrium condition, along which stands travel during the course of self-thinning.

During the past two decades the rule has been considered a basic principle of universal applicability, - regardless of species, site, etc. However, this has recently been questioned (e.g. Zeide 1987), and it has been pointed out that, in general, the graph is more likely to be curve.

There have been various attempts to put the rule into practice (e.g. Drew & Flewelling 1977, 1979), but the rule provides only summary information about a stand. The forest district officer would for instance benefit more by information about the distribution of volume by diameter class. The study of population structure of unthinned stands provides some useful guidelines.

POPULATION STRUCTURE

Size differentiation in a stand of trees is one of the basic processes which characterize the stand development. The differentiation is due to initial differences in size as well as to competetive interaction. When growth depends on the size of the individual relative to others in the stand, the increment pattern of a given measure is closely related to the shape of the frequency distribution of that same measure (Hara 1984, Westoby 1982). The function relating the increment of a size measure to the same size measure, across all individuals in the stand at a point in time, has been termed a distribution-modifying function (Westoby l.c.). The increment of DBH graphed against DBH is an example of a DMF. The shape parameters of a frequency distribution are affected by the shape of its DMF. Let the DMF be described by polynomials in x. A DMF described by a constant (x^0) affects only the first moment of the frequency distribution, i.e. the mean. A DMF described with a term in x^1 (straight line) affects the second moment, i.e. the standard deviation. With a term in x^2 (parabola) the third moment is affected, i.e the skewness. And with a term in x^3 (sigmoid curve) also the fourth moment is affected, i.e. the kurtosis.

MATERIAL AND METHODS

The study material was an unthinned plot in a thinning experiment with Sitka spruce (sample plot MF, parcel a_1) and the results from another thinning experiment (sample plot MB, parcels d and k, reported by Henriksen (1961)). Both experiments are located in dune forests in northwestern Jutland, near the North Sea. They have been measured at regular intervals throughout the years. Some single observations from other stands have been used, too.

The diameter increment and the diameter distribution of sample plot MF is analysed and, in the light of the above mentioned theory, compared to the normal distribution. The analysis comprises the period from age 28 - 56 years. 1-cm classes are used. Results are related to the volume distribution, in order to provide the forest district officer with a tool for predicting end-use volume by means of easy-made assesments/measurings. Further, the self-thinning in both sample plots are evaluated in the light of the self-thinning rule.

RESULTS

DIAMETER DISTRIBUTION

The diameter distribution (figure 1) develops from being skewed to the left to being slightly skewed to the right, and it broadens out. When following skewness to the left, skewness to the right is supposed to indicate the onset of self-thinning (Mohler et al. 1978). Further, it is visually clear that a bimodality appears, already at the height of approx. 11 m. From then onwards, the diameter corresponding to mean basal area is consistently located in the depression between the 2 modes. D_g is probably a usable criterion to separate 2 storeys in an unthinned stand.

Test statistics (figure 2) support these observations. But, as judged by the significance levels, the appearance of significant bimodality is far later than visually observed. Bimodality as such is, however, not a testable property. For that purpose, a test for a compound distribution is more suitable. (A priori estimates of expected parameters needed). Furthermore, the degree of bimodality is dependent upon the number of class intervals.

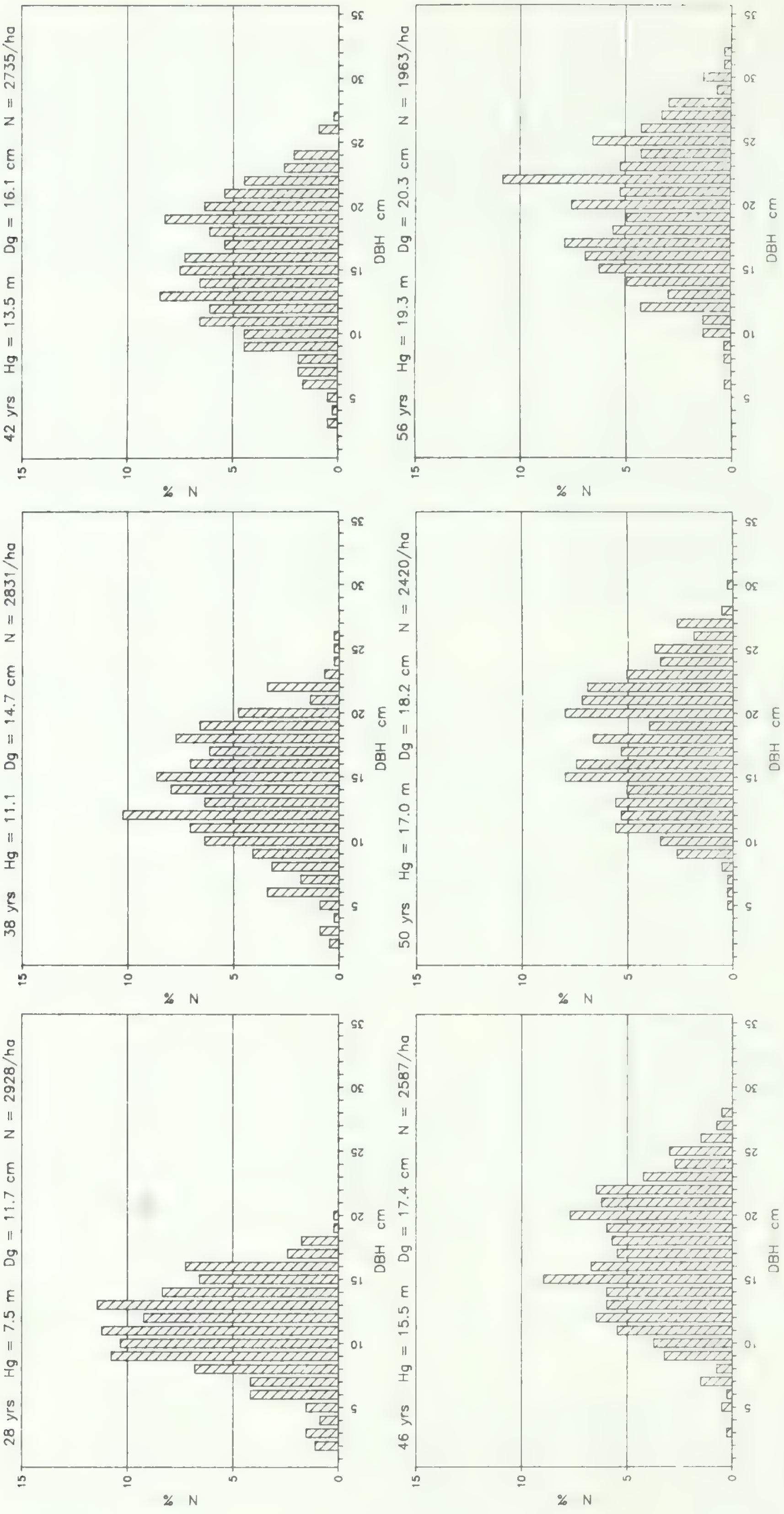


Figure 1. Sample plot MF, parcel a_1.
Selected diameter distributions; age 28 - 56 years from seed. H_g = height corresponding to mean basal area, N = stem number, D_g = diameter corresp. to mean basal area.

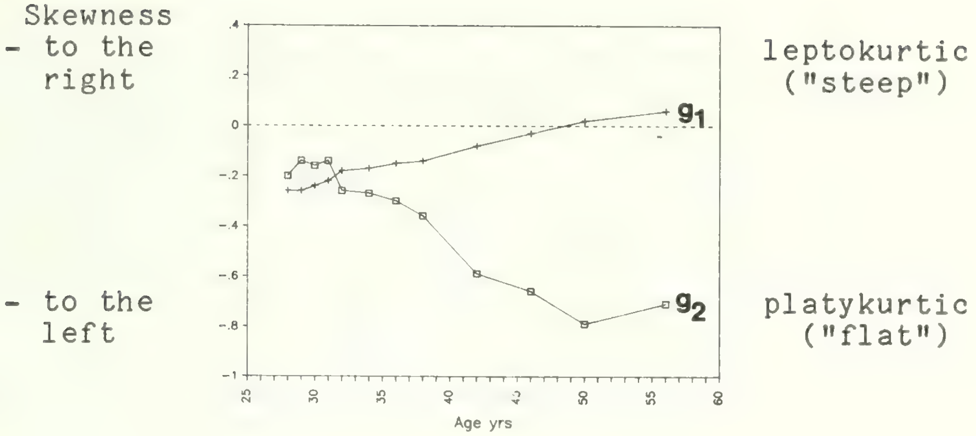
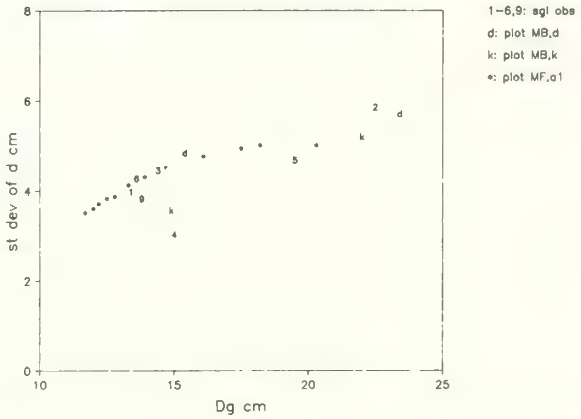


Figure 2. Sample plot MF, parcel a_1. Development in skew, g_1, and kurtosis, g_2. $g_1 = g_2 = 0$ corresponds to the normal distribution. g_1 is significantly different from 0 for ages 28, 29 and 30 years (95%-level), g_2 is significantly different from 0 for ages 46, 50 and 56 years.

Note, that the distribution has become less platykurtic lately. The density dependent mortality apparently compensates for the competitive growth differentiation. Accordingly, the standard deviation, s_d, seems to reach an upper asymptote (figure 3). Maybe this tentative curve of s_d as a function of D_g is universal to some degree, irrespective of spacing and site class (Henriksen (1958) supports this view).

Figure 3. Standard deviation on DBH, s_d, graphed against D_g.



A chi-square test for goodness-of-fit gives no unequivocal results. That may be due to development of a compound distribution.

DIAMETER INCREMENT

The increment analysis (figure 4) is based on the relative diameter growth rate, computed as means for each 1-cm class. The use of RDGR eliminates the influence of the diameter itself. Indications of competitive interactions are apparent already at the height of approx. 8 m. It is characteristic that the increment of small trees decrease to a very low level (almost zero) while larger ones grow persistently. This creates a two-storeyed stand. The sigmoide increment curves support the presence of bimodality, though there is a time lag. The lag is even more pronounced for the development of a skewness to the right.

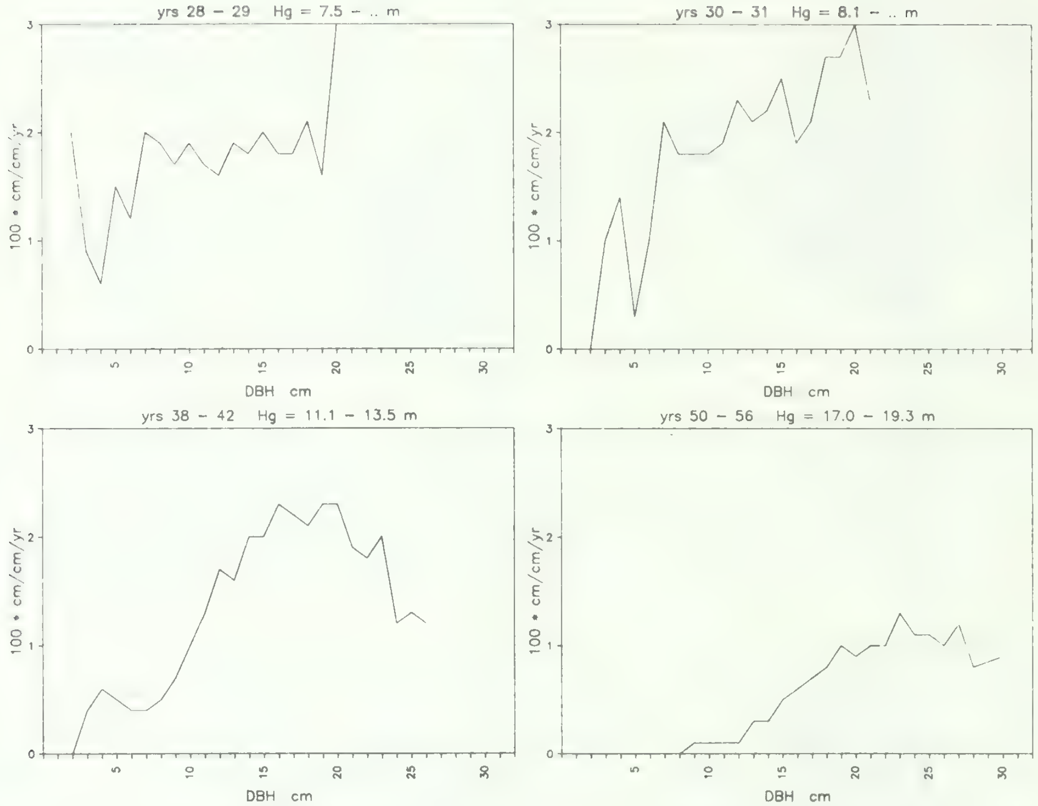


Figure 4. Sample plot MF, parcel a_1. Relative diameter growth rate in selected periods. Computed as mean RDGR for each 1-cm class.

VOLUME DISTRIBUTION

We have seen that D_g is located in the depression between the 2 modes in the diameter distribution. The value of D_g in prognoses depends on the distribution of volume in relation to D_g, and the development in the volume distribution.

In sample plot MF, a final structure had developed already at a height of approx. 13 m (table 1). From that time, total stemwood with DBH > D_g amounts to approx. 73% of total stand volume. These findings are confirmed when analysing other stands (sample plot MB and single observations). Reducing the figures to merchantable volume causes a shift in favour of the larger dimensions.

Table 1.
Sample plot MF, parcel a_1.
Volume distribution by diameter class, %.

Age yrs	H_g m	D_g cm	DBH cm 0-4	5-9	10-14	15-19	20-24	25-29	30-34	Summary $<D_g$	$>D_g$
28	7.5	11.7	-	8	51	41				33.6	66.4
42	13.5	16.1	-	2	16	38	41	3		27.1	72.9
50	17.0	18.3			9	25	45	21		28.0	72.0
56	19.3	20.3			5	21	38	32	5	25.5	74.5

THE SELF-THINNING RULE

The validity of the self-thinning rule has been tested with data from the 3 permanent plots. Variables are stand volume and stem number. In sample plot MF, parcel a_1, the reduction in stem number per ha is from 2928 to 1963. In sample plot MB, parcel d, there is a reduction from 2468 to 1353, and in parcel k a reduction from 2660 to 2077. Thus it is clear that there has been substantial density dependent mortality in all 3 plots. (It is found to take place among the smaller trees). Further, it should be noted that the volume increment in sample plot MB is among the highest on record in Denmark: standing volume approx. 1000 m^3/ha when terminated! No larger volume accummulation can be expected in this country.

For convenience, let us express the self-thinning rule (equation 2) in more general terms:

$$V = kN^{-a} \qquad (5)$$

where symbols are as earlier explained and a is the self-thinning exponent.

It appears that data are in disagreement with the traditional self-thinning rule (figure 5). Principal component analysis, on logarithmically transformed data from the time when mortality sets in, reveal self-thinning exponents -0.96, -0.95 and -0.98 for plots MF-a_1, MB-d and MB-k respectively. Consequently, this material shows a considerably more steep self-thinning line than expected. Others have reported similar results recently (e.g. Wannamaker & Carleton 1982, Zeide 1987).

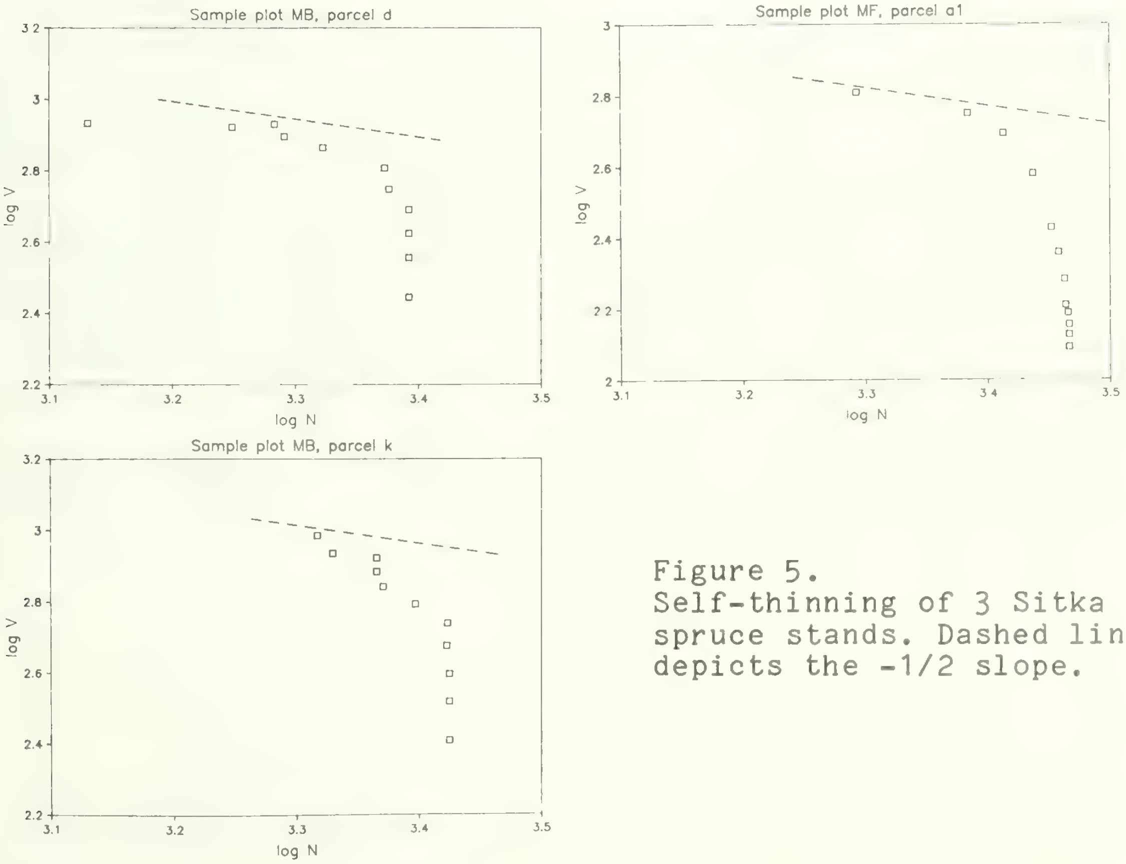


Figure 5.
Self-thinning of 3 Sitka spruce stands. Dashed line depicts the -1/2 slope.

DISCUSSION

The analysis shows, that Sitka spruce in Denmark, undergoing self-thinning, does neither fully conform to the self-thinning rule nor to the expected associated changes in population structure.

As judged by the skewness of the diameter distribution and the slope of the thinning line, the stands examined reach the self-thinning phase very late in life, if ever. There is, however, substantial evidence that competitive interaction has taken place and that stands have been thinning themselves for a long time. Stem number reductions from 20-45% is one point. Furthermore, the increment analysis clearly demonstrates the establishment of a hierarchy of dominance and suppression. The appearance of bimodality in the diameter distribution also indicates the development of a 2-storeyed stand. Thus, it seems that the occurence of bimodality is a clear indication of competitive interaction. However, this issue is controversial; some research workers share the view stated here (e.g. Ford 1975), while others question whether bimodality is typical or even common in the real world (e.g. Westoby 1984). As to the self-thinning rule, the data presented here support a rejection of the rule in its original formulation (equations 1, 2, 4). For various reasons, which I shall not discuss here - and when viewing figure 5, a self-thinning curve seems more appropriate than a straight line (see for example Zeide 1987).

It is demonstrated that in closed stands, the diameter corresponding to mean basal area is consistently located in the bimodality depression. And shortly after canopy closure the volume distribution develops a final structure as regards to D_g: 73% of yield having a DBH > D_g. This makes it easy for the forester to predict an approximate distribution of end-use volume. Few measures are needed to get an estimate of D_g and even fewer to get an idea of the maximum diameter in a stand. Early predictions require a yield table, of course. Usable tables for unthinned stands remain to be prepared: Sitka spruce in Denmark does not obey the Eichhorn rule, and therefore available tables (e.g. Hamilton & Christie 1974, Henriksen 1958) are not satisfactory. It should be noted, that when actually walking in an unthinned stand the 2 storeys are not necessarily observable by the eye!

Finally, I must disclose, that with a no-thinning regime applied to the Sitka spruce, acceptable dimensions and quality of yield are achievable within a reasonable space of time. Further details on this issue will be published elsewhere.

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COMPATIBLE GROWTH MODELS AND STAND DENSITY DIAGRAMS

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ABSTRACT. A stand average growth model based on the self-thinning rule is developed and used to generate stand density diagrams. The model is tested on plantation data from 15 remeasured red pine (Pinus resinosa Ait.) permanent sample plots. For total stem volume (m^3/ha.) versus numbers of stems per ha. the slope was 1.39 and the intercept 10350 m^3/ha/tree. Incipient mortality occurred at a relative density (RD) of 0.04, maximum current annual increment at 0.51 RD and maximum mean annual increment at 0.82 RD. Diameter distributions were 'recovered' from any point on the diagram using the weibull distribution.

INTRODUCTION

The self-thinning rule (Yoda et al., 1963; Westoby, 1984) has been advocated as a useful measure of the maximum expression of mean or total stand biomass or volume for a given number of surviving stems per unit area. Others (Weller, 1987; Zeide, 1987) question this assertion and are especially critical of the fitting and data selection procedures. Stand density diagrams (sensu Drew and Flewelling, 1979) are based explicitly on the self-thinning rule and have been used to assist in silvicultural planning. Stand density diagrams capture graphically the relationship between volume, quadratic diameter, dominant height and stems per unit area. Stand density diagrams are static representations of stand dynamics; a dynamic component can be added by using height growth curves or growth models. Usually these dynamic and static components are not entirely compatible. Data sets often differ as do model assumptions.

The objective of this paper is to see if it is reasonably and statistically possible to develop a growth model based on the self-thinning rule that also generates stand density diagrams. A red pine data set is used to test model assumptions.

MODEL DEVELOPMENT

The self-thinning rule may be represented as:

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$$\ln(Y_m) = \ln(a_1) - a_2 \ln(N_i) \qquad (1)$$

where Y_m = maximum attainable total or mean size, N_i = surviving stems per unit area, a_1 is the intercept and a_2 the slope of the relationship. For average total stem volume the slope is thought to be approximately 3/2 for a wide range of species (White, 1981) although it has been hypothesized that the intercept varies with species tolerance (Harper, 1977).

Methods for fitting (1) have varied from subjectively placing a line above an upper scatter of points while assuming a slope of -3/2 (e.g. Drew and Flewelling 1977), linear regression (e.g. Yoda et al. 1963), principal components analysis (Mohler et al. 1978). More recently the asymptotic nature of the self-thinning line (1) has been modelled (e.g. Hara, 1984; Lloyd and Harms 1986).

If indeed the process of self-thinning is asymptotic in nature (White 1981) then this should be incorporated in the modelling process. Thus we can include stands that are not close to an hypothesized asymptote. This step makes it irrelevant as to whether we are modelling total or average stand volume. This is because we switch the focus of our modelling from maximum potential to actual volume or biomass. Smith and Hann (1984, 1986) and Smith (1986) have developed a general framework for the asymptotic modelling of self-thinning stands. These ideas are extended in this paper.

The approach towards the self-thinning asymptote may be given by a logarithmic form of a Chapman-Richards type equation, (2):

$$\ln(Y_1)=\ln(a_1) - a_2 \ln(N_i) + a_3\ln(1- a_4\mathrm{EXP}(-a_5(\ln(N_0/N_i)) \qquad (2)$$

where symbols are as in (1), N_0 is initial number of stems per unit area and a_3, a_4 and a_5 are parameters. The point just before the first tree dies due to competition may be envisaged as approximate crown closure and is given by (3):

$$\ln(Y_0)=\ln(a_1) - a_2 \ln(N_i) + a_3\ln(1- a_4) \qquad (3)$$

where symbols are as in (1) and (2) and Y_0 = size at crown closure. Relative density (RD) may be defined as the actual number of stems divided by the maximum number of stems for a given mean stem volume (Drew and Flewelling, 1979; Smith and Hann, 1986). Thus RD at approximate crown closure reduces to (4):

$$RD_{cc} = \mathrm{EXP}(a_3 \ln(1- a_4)) \qquad (4)$$

where RD_{cc} = relative density at approximate crown closure.

It is possible to test the effects of site index and initial spacing on any of the parameters in (2) by adding indicator variables.

Model (2) may be termed an analytical size density model. Adding a dynamic component to this model is a two-staged nonlinear modelling process achieved by fitting numbers of stems as a function of time, site productivity and initial spacing, (5), and then fitting this model into (2):

$$\ln(N_i)=\ln(b_1) + \ln(1-(1-EXP(-(t-t_0)\ b_2))^{b_3}) \tag{5}$$

where b_1 is stems per unit area at approximate crown closure, t is time since planting, t_0 is time of approximate crown closure and b_2 and b_3 are parameters.

METHODS

A red pine plantation data set mostly from the Petawawa National Forestry Institute, Ontario, Canada was used. (See Berry 1984). Mean initial spacing was 2884 sph (range 608-6193), mean age 31.5 yrs since planting (range 10- 63) and mean site index (top height in meters at 25 years since planting) was 13.6 (range 11.6-15.8). The mean number of remeasurements was 5.1 (range 3-8). Four stands had been respaced at an early age. Only measurements since this time were included. One stand was subject to vandalism; only measurements prior to this were used. Two stands were measured prior to approximate crown closure (defined by equations given in Smith and Hann (1986)). Pre-crown closure measurements were ignored. This gave a total of 76 data points.

First, each stand was fit to (5). The parameter estimates t_0, b_2 and b_3 were fit as multiple linear functions of site index and initial spacing. The parameters b_2 and b_3 were then refit to the full model using the multiple regression estimates as initial values. All models were tested at the 0.01 probability level in any significance test. Next, the size-density model (2) was fit to the data. Slope and intercept estimates were tested for effects of site index using dummy variables. The results of this analysis are not reported here but are essentially similar to the results presented in Smith and Hann (1984). The size-density model was converted into a growth model by using estimated stems per ha. from (5). Mean total stem volume, quadratic mean diameter and top height were all fit in this manner. A stand density diagram was constructed using the procedures in Smith (1986). All models were weighted by the total number of measurements per stand.

Finally a three parameter weibull distribution was generated for the diameter distribution for each stand at each measurement. The location parameter was estimated directly, while the scale and shape parameters were estimated using the 24th and 93rd percentile values. (Clutter et al. 1983) It was hypothesized that each point on the density diagram had an associated unique diameter distribution for unthinned stands. The three parameter weibull estimates for diameter distributions were fit using the following general model forms: location parameter (a) = $f(RD,N_i,N_0)$, scale parameter (b) = $f(a,RD,N_i,N_0)$ and shape parameter (c) = $f(b,RD,N_i,N_0)$. For the purposes of these analyses the weibull parameters were not constrained to produce compatibility between observed and predicted quadratic diamters.

RESULTS

TABLE 1. Parameter estimates for equation (2)

	DEPENDENT VARIABLES			
Parameters	V_i	$\hat{V}_i$	qd	ht
a_1	10.077	9.245	7.360	5.645
a_2	1.470	1.393	0.594	0.325
a_3	0.390	0.845	0.406	0.390
a_4	0.996	0.975	0.905	0.975
a_5	1.441	10.372	28.386	4.378
MSE	1.841	0.414	0.070	0.0656
Equation no	8	9	10	11

Note: abbreviations in text. V_i is estimated using actual sph and $\hat{V}_i$ is estimated using predicted sph from (6).

The final survival model was:

$$\ln(V_i)=\ln(N_0)+\log(1-(1-\mathrm{EXP}[-(t-t_0)\cdot 0.0004\ \ln(N_0)\ \ln(SI)^2])^{(0.1269\ \ln(N_0)\ \ln(SI))}) \quad (6)$$

where symbols are as in (5), and SI is site index (top height at 25 yrs since planting), mean squared error (MSE) is 0.0347 and number of observations is 76. The location parameter t_0 was estimated as:

$$\ln(t_0)=-34.6+5.502\ \ln(N_0)+17.637\ \ln(SI)-2.584(\ln(N_0)\cdot\ln(SI)) \tag{7}$$

where parameters are as above , MSE is 0.014 and adjusted R^2 0.97.

The fits for (2) using both actual and estimated N_i are given in table 1. Figure 1 shows a plot of the log-log relationship between mean total stem volume and stems per ha. Figure 2 shows a stand density diagram for the red pine data set.

The weibull diameter distribution parameter estimates were:

$$\ln(a)=8.088+2.313\ RD-0.812\ Rd^2-0.958\ \ln(N_i)$$

$$\ln(b)=10.518-0.597\ \ln(a)-0.211(1/RD)+0.354\ RD^3-0.892\ \ln(N_0)$$

$$\ln(c)=-0.966+1.817\ \ln(b)-0.285\ \ln^2(b)-1.037\ RD^2+0.324\ RD^3$$

where a,b, and c are weibull location, scale and shape parameters, RD is relative density, N_i is stems per ha. and N_0 is initial stems per ha.. The R^2 for each equation was 0.905, 0.820 and 0.721 and MSE's were 0.059, 0.022 and 0.027, respectively. The weighted R^2 for the system of equations was 0.877.

DISCUSSION

The model forms presented here allow the testing of various hypotheses about stand development. The slope estimate (equation (9)) was not significantly different from 3/2. All parameter estimates were significant leading to the conclusion that a self-thinning asymptote does exist for red pine and may be used as the basis for growth modelling. The same model could be used to test if the asymptotic condition tends to be curvilinear. Several researchers note that the self-thinning phase is transitory and that stands break up and fall away from the self-thinning asymptote (Harper 1977, Lloyd and Harms 1986). There were not enough data to test this relationship for red pine. It should be also be statistically feasible to test this observation by slightly modifying the modelling approach used here.

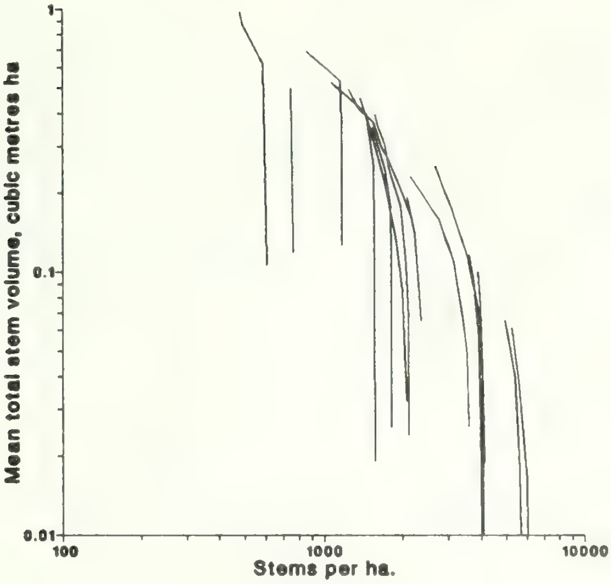

Figure 1. Volume-density relationships for red pine permanent sample plots

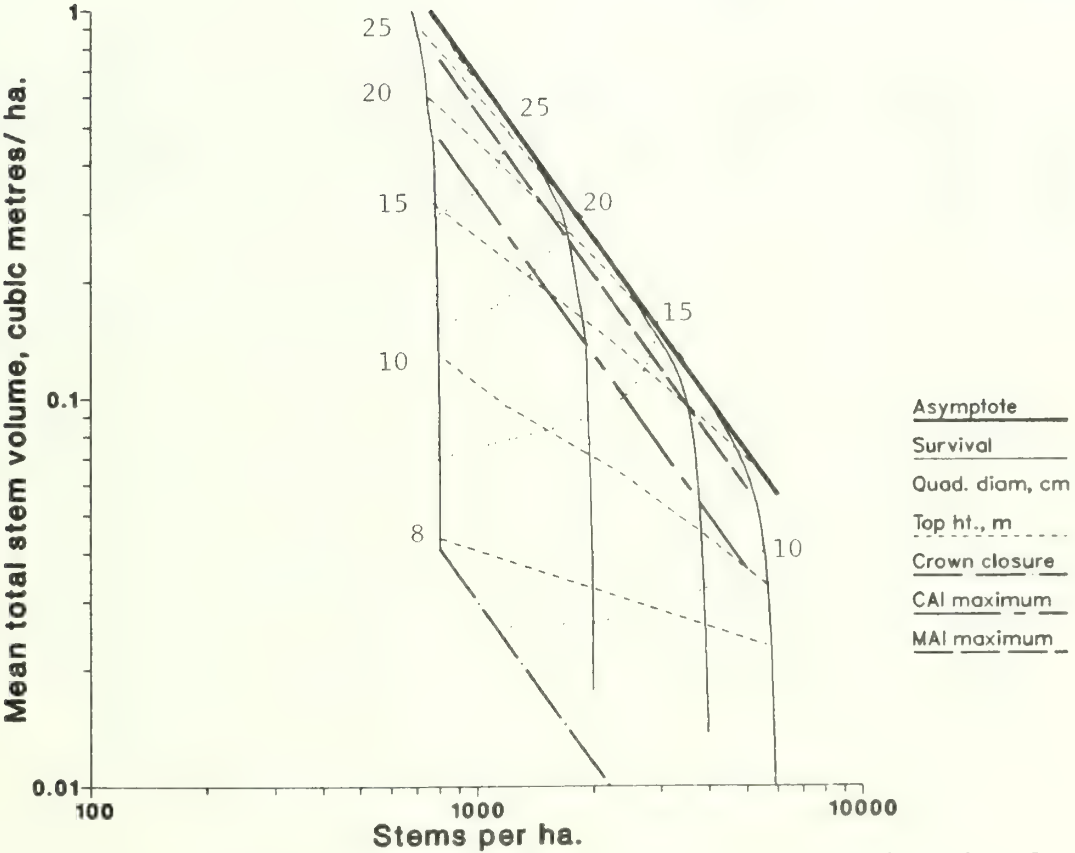

Figure 2. Stand density diagram for red pine. All relationships from equation 9, except diameter (equation 10) and height (equation 11)

It has been argued that a stand density diagram represents the mathematical combination between size and number in self-thinning stands (Drew and Flewelling 1979). Thus it is reasonable to hypothesise that one diagram is relevant irrespective of site, age and location. Again this may be tested using the model form presented here. Because of the very restricted data base used for these analyses, however, our parameter esimates are valid only for the Petawawa National Forestry Institute. In particular the densely planted stands had lower total volume per ha. giving lower volume estimates at higher densities.

The stand density diagram can be used for silvicultural prescriptions. For instance, the approximate crown closure line indicates at what point intratree competition sets in. Stands should be thinned at RD 0.51 so as to maintain per unit area growth rates. Stands should be harvested at RD 0.82 if the objective is to maximize mean annual increment. The diagram may be used when access to a computer is limited or inconvenient. More precise estimates can be had via a computerized growth model.

The hypothesis was tested that a unique diameter distribution exists for each point on the stand density diagram.(These same ideas could be tested on any size measure distribution (e.g. volume, crown ratio etc.)). The simultaneous approach used , and reasonable fits to the data do indicate that such a relationship exists. The additions of site index and age were not significant.

The stand density diagram has some advantages over just height or diameter stocking guidelines. It includes information on volume as well. The final result is a stand average growth model with size distribution recovery capabilities.

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EFFECTS OF STAND DENSITY ON THE INCREMENTS OF TREES IN AN EVEN-AGED PURE STAND

Tanaka K.[1]

ABSTRACT. Differences in periodic increments of trees at a given age were analyzed using data from three Sugi (Cryptomeria japonica D. Don) plots of different stand density. In a graph the vertical axis of which is periodic increment and horizontal axis is the size of tree at the beginning of the period, both diameter and height growth showed a positive linear relationship between periodic increment and the size of tree. But the effects of stand density on this relationship were different for diameter and height growth. In the case of diameter growth, stand density had an effect on the constant term of the regression line. However, in the case of height growth, it affected both the two regression coefficients.

INTRODUCTION

Forest stands, even if they are even-aged, consist of trees of different sizes and different increments. In order to understand stand growth, the analysis of differences in increments of trees at a given age, as well as the analysis of changes in increments of trees with stand age, is important. Not only total and average increment but also distributional information is needed for yield prediction. Therefore, it is necessary to clarify the mechanism of the division of stand growth among trees.

Differences in the periodic increments of trees in a given period are often analyzed using a graph the vertical axis of which is periodic increment and the horizontal axis is size of tree at the beginning of the period. In the case of diameter growth in an even-aged pure stand, there is a positive linear relationship between periodic diameter increment and diameter at a given forest age, that is, trees of larger diameter have a larger periodic diameter increment at a given age (Prodan, 1951). According to the results of a previous analysis of the growth of a main crop of Sugi, the slope of the regression line of periodic diameter increment on diameter at a given forest age was found to be steep in the early years, and became gentler as forest age increased. Where there was found to be a linear relationship between the mean diameter and the intersection of the regression line with the diameter axis, the value of this intersection increased as forest age increased (Tanaka, 1986).

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On the other hand, according to the results of the analysis of the growth of other even-aged pure stands of Sugi or Hinoki (Chamaecyparis obtusa S. et. Z.), no correlation was found between periodic height increment and height at a given forest age. That is to say, the regression line describing height growth was almost parallel to the horizontal axis (Tanaka, submitted).

As outlined above, the relationship between periodic increment and size at the beginning of a period in an even-aged pure stand is partially understood. However, the effects of thinning on the above relationship is still unknown. Analysis of data from some thinned experimental plots has shown no clear relationship and so the effects of thinning on tree growth could not be ascertained. This paper will consider the effects of thinning on tree growth using the results of an analysis of the growth records of stands which exhibited extreme variations in stand density.

DATA

The data used were survey results from three plots in the even-aged pure stands of Sugi in the Ninosawa Sugi Experimental Plot of the Tokyo University Forest in Chiba Prefecture. These experimental plots were established in 1966 with different densities, that is, normal density, high density and extra-high density. Enumeration surveys were carried out five times from 1980 to 1986. Diameters were measured at a height of 1.3 m using calipers, two measurements at right angles to each other being taken and rounded to the nearest 0.1 cm. Heights were measured with a graduated pole and rounded to the nearest 0.01 m.

TABLE 1. Results of two surveys.

Plot	normal density		high density		extra-high density	
Year of survey	1980	1986	1980	1986	1980	1986
Age (year)	14	20	14	20	14	20
Number of trees per plot	69	67	161	149	266	209
Stand density (trees/ha)	3378	3281	7133	6602	12299	9664
Mortality (%)	2.9		7.5		21.4	
Statistics of diameter distribution						
Mean (cm)	10.2	14.0	7.4	10.0	7.3	9.5
Variance (cm^2)	5.55	11.42	4.07	8.34	4.02	6.46
Coef. of var. (%)	23.0	24.1	27.1	29.0	27.5	26.7
Skewness	-0.36	-0.30	-0.05	-0.03	0.22	0.46**
Basal area (m^2/ha)	29.3	53.4	33.3	55.8	55.1	73.7
Statistics of height distribution						
Mean (m)	8.4	12.2	6.7	9.6	7.4	10.3
Variance (m^2)	2.01	3.90	2.13	4.17	1.99	3.05
Coef. of var. (%)	16.8	16.2	21.6	21.2	19.1	17.0
Skewness	-0.84**	-1.06**	-0.49*	-0.71**	-0.60**	-0.57**

* Significant at 5 % level; ** highly significant at 1 % level.

This paper analyzes the data from the 1980 and 1986 surveys. Table 1 shows the results of the surveys in 1980 and 1986. The diameter distributions were similar to the normal distribution except for the extra-high density plot having a slight positive skewness. The coefficients of variation of the diameter distributions were almost 25 % regardless of density. The lower density plot had a larger average diameter but smaller basal area. These tendencies are general characteristics of the diameter distribution in even-aged pure stands.

The height distributions were skewed negatively, that is, they showed a so-cold J-shaped distribution. This tendency is also a general characteristic of the height distribution in even-aged pure stands. The lower density plot had a smaller skewness in the height distribution, that is, it was more noticeably J-shaped. The J-shaped height distribution can be thought of as originating from the existence of trees in the lower story which usually are behind the trees in the upper story in terms of growth. Since trees in the lower story of a lower density stand suffer less suppression, their probability of survival is higher than that of lower story trees in a higher density stand. Therefore, the lower density plot's height distribution ought to have a smaller skewness.

The data from trees in the upper story were used in the analysis of the relationship between periodic increment and the size of tree at the beginning of a period. Trees in the lower story might be behind the others in terms of growth because of suppression, therefore, they will have quite different growth patterns to those of trees in the upper story.

The way used to determine the boundary between the upper and lower stories, which worked well in a previous paper (Tanaka, 1983), can be outlined as follows. First, define the smallest tree as the lower story, and calculate the skewness of the height distribution of trees in the upper story, that is, all trees has the smallest. Next, define the lower story as the two smallest trees and recalculate the skewness of height distribution in the upper story. Continue this process and, in this way, all possible boundaries between the upper and lower stories can be defined and the corresponding skewnesses of the height distribution in the upper stories calculated. The desired boundary is that boundary where the absolute value of the skewness of the height distribution of the trees in the upper story is the smallest.

RESULTS

EFFECT OF STAND DENSITY ON DIAMETER INCREMENT

Before the analysis, the means and variances of the periodic diameter increments from 14 to 20 years were calculated by diameter classes (2cm) at 14 years, and checked to ascertain whether the calculated values contradicted the hypotheses of the stochastic diameter growth model outlined above (Tanaka, 1986). It was confirmed that there was a positive linear relationship between periodic diameter increment and diameter at a given age, and that the variance of the periodic diameter increment was approximately constant and, therefore, independent of diameter.

Figure 1 shows the regression lines of periodic diameter increment on diameter at the beginning of the period. The slope of the regression lines were almost the same, about 0.45, regardless of stand density. The constant term of the regression line in the higher density plot was smaller. Thus, the regression lines calculated by plot formed a group of parallel lines, with higher density plots represented by the lower lines in the Figure 1.

Figure 2 shows the relationship between the intersection of the regression line with the diameter axis and the basal area at the beginning of the period. It is thought that Figure 2 shows that there is a fairy close relationship between the value at this intersection and basal area. However, since there are only three points, namely those representing the normal, high, and extra-high density plots, we can only tentatively conclude this.

From the results above, it is concluded that the effect of stand density on the diameter increments of trees in even-age pure stands appears through changes in the constant term of a regression line of periodic diameter increment on diameter.

TABLE 2. Results of regression analyses.

Plot		normal density	high density	extra-high density
Age at the beginning of the period	(year)	14	14	14
Age at the end of the period	(year)	20	20	20
Increment of diameter				
Number of trees analyzed	(trees)	63	141	205
Slope of regression line	(cm per 6yrs/cm)	0.454	0.450	0.472
Constant term of regression line	(cm/6yr)	-1.07	-1.14	-2.14
Intersection with diameter axis	(cm)	2.3	2.5	4.5
Unbiased variance of residual	($(cm/6yr)^2$)	0.87	0.68	0.52
Standard deviation of increment from regression line	(cm/6yr)	0.93	0.82	0.72
Coefficient of determination		0.483	0.470	0.533
Mean diameter at 14 years	(cm)	10.7	7.9	8.0
Mean of diameter increment	(cm/6yr)	3.8	2.4	1.6
Increment of height				
Number of trees analyzed	(trees)	63	140	204
Slope of regression line	(m per 6yrs/m)	0.352	0.389	0.567
Constant term of regression line	(m/6yr)	0.71	0.06	-2.08
Intersection with height axis	(m)	-2.0	-0.2	3.7
Unbiased variance of residual	($(m/6yr)^2$)	0.31	0.39	0.47
Standard deviation of increment from regression line	(m/6yr)	0.56	0.62	0.68
Coefficient of determination		0.301	0.332	0.380
Mean height at 14 years	(m)	8.7	7.1	7.9
Mean of height increment	(m/6yr)	3.8	2.8	2.4

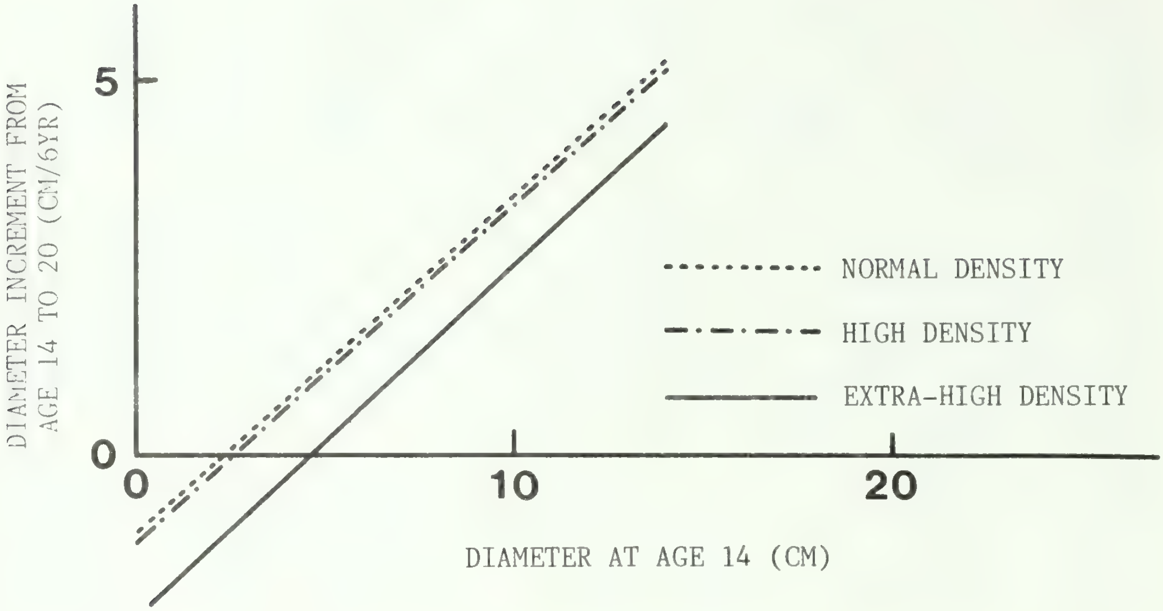

Figure 1. Regression lines of the periodic diameter increment on diameter at the beginning of the period.

Statistics are given in Table 2.

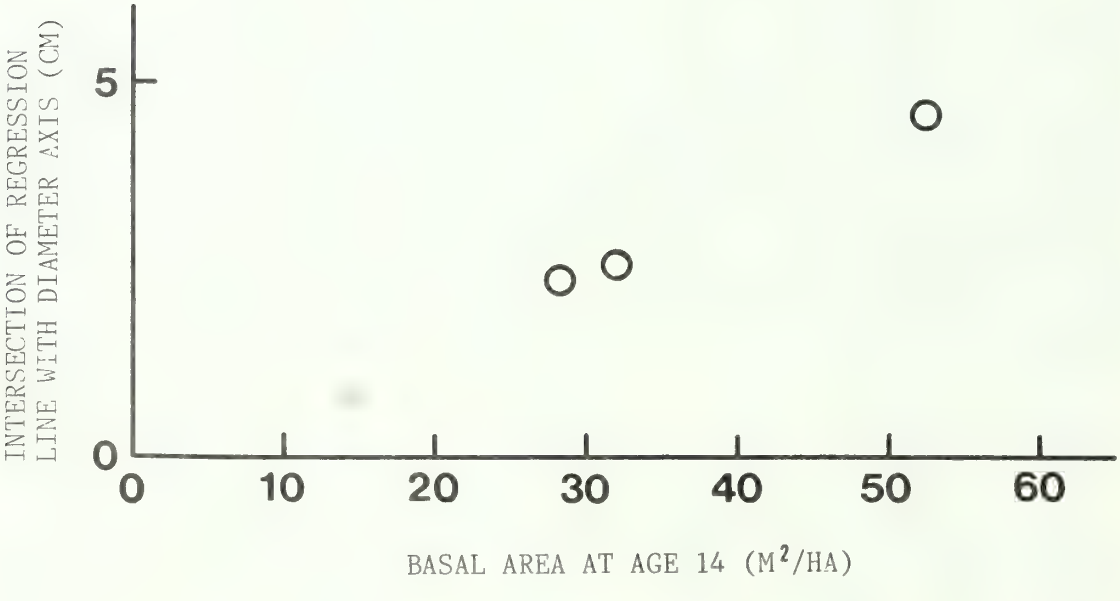

Figure 2. Relationship between the intersection of the regression line with the diameter axis and the basal area at the beginning of the period.

EFFECT OF STAND DENSITY ON HEIGHT INCREMENT

As in the analysis of diameter increment, the means and variances of the periodic height increments from 14 to 20 years were calculated by height class (1m) at 14 years, and compared with the predictions of the hypotheses of the stochastic height growth model mentioned earlier (Tanaka, submitted). The results differed somewhat from those reported in the earlier paper as a positive linear relationship between periodic height increment and height at a given age was found. The variance of height increment was approximately constant.

Figure 3 shows the regression lines of the periodic height increment on height at the beginning of the period. The slope of the regression line was greater in higher density stands, and the intersection of the regression line with the height axis moved rightward in higher density stands. The effect of stand density differed between height increment and diameter increment.

In a previous paper (Tanaka, submitted), where the data used came from plots where stand density was lower than that of these experimental plots, the slope of the regression line of the periodic height increment on height at the beginning of the period was almost zero. In other words, height increment was independent of stand height.

The reduction in the number of trees over the period, which was bigger in the higher density stands, was caused chiefly by the intraspecies

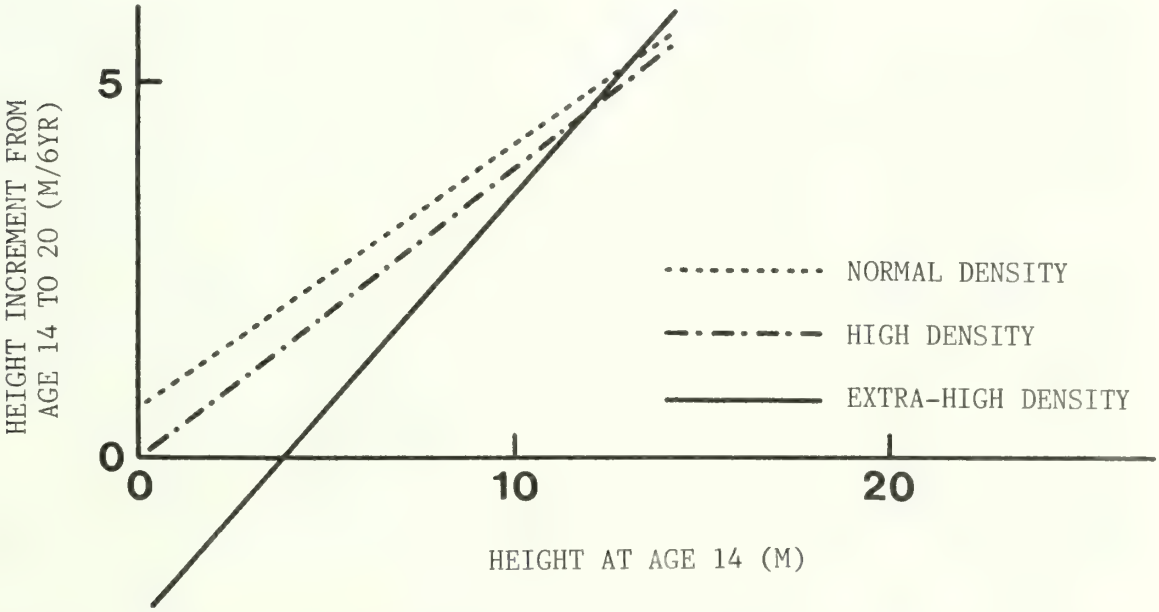

Figure 3. Regression lines of the periodic height increment on height at the beginning of the period.

Statistics are given in Table 2.

competition. As stand density becomes greater, the longitudinal increment of smaller trees might be affected to a greater extent. The micro-climatic and environmental conditions might be more stressful for trees below a certain height level. This critical height is probably greater in higher density stands. Therefore, the intersection of the regression line with the height axis might be located further to the right (i.e. at a greater height) in higher density stands.

On the other hand, taller trees suffer less suppression from the other trees and are therefore less affected in terms of longitudinal increment. Specifically, the height increment of the tallest trees is thought to be less affected by stand density.

As the degree of suppression of smaller trees in higher density stands is thought to be more marked and the intersection of the regression line describing higher density stands is further to the right, the slope of regression line for higher density stands ought to be steeper.

From the results above, it is concluded that the effects of stand density on the height increments of trees in even-aged pure stands appear in both coefficients, that is the slope and the constant term, of the regression line of the periodic height increment on height.

DISCUSSION

MECHANISM OF TREE GROWTH AND EFFECT OF STAND DENSITY

In the cases of both diameter and height growth, a positive linear relationship between periodic increment and the size of tree at the beginning of the period was found. But effect of stand density on this relationship was different for diameter and height growth. In the case of diameter growth, stand density chiefly had an effect on the constant term of the regression line. However, in the case of height growth, it affected both regression coefficients.

The linear relationship between periodic diameter increment and diameter is considered to be caused by the difference in the amount of cambium. The amount of cambium is almost proportional to the circumference of the trunk, which means it is also almost proportional to the diameter. If we assume that the amount of cell division per unit cell is approximately the same in an even-aged pure stand at a given forest age, trees of larger diameter will have the larger periodic diameter increment.

On the other hand, the amount of apical meristem seems to be almost the same in different trees in a stand regardless of height. This may be the reason for the lack of any correlation between periodic height increment and height in a stand of lower density where there is no intraspecies competition. In a stand of higher density, smaller trees suffer more suppression and are more affected in their longitudinal increment. This may be the reason for both the appearance of a linear relationship between height increment and height and the tendency for the regression line in higher density stands to be steeper.

Although both diameter and height growth showed a positive linear relationship between increment and size, the causes of these relationships are believed to be essentially different. This difference may be the reason for the differing responses of tree growth to stand density.

INFERENCE ABOUT THE EFFECT OF THINNING ON TREE GROWTH

Here we will infer the effects of thinning on tree growth from the conclusions drawn above as to the effect of stand density on tree growth in an even-aged stand. In actual commercial forests, stand density is usually between 3000 and 4500 trees per hectare at planting, and falls to between 1500 and 3000 trees per hectare at the age of 20 years because of thinning. Generally speaking, commercial forests have lower in stand densities than that of the experimental plot in this paper. Therefore, as the results of a previous paper showed, it might be thought that the periodic height increment is almost constant and independent of height in even-aged commercial stands at a given forest age (Tanaka, submitted). In other words, we might be able to disregard the effect of thinning on the height increment in a commercial stand.

On the other hand, it is known that diameter increment is promoted by thinning operations. Because of the lowering of stand density by thinning the regression line in Figure 1 will move left-wards. However, some years might be necessary before the effects of thinning finally work themselves through and so the movement of the regression line during this transitional period will not necessarily be always such that the slope remains unaltered. Finally, however, the regression line will become parallel to the regression line describing conditions before thinning. For prediction of forest growth, it is necessary to understand the pattern of the movement of this regression line. Although basal area is closely related to the intersection of the regression line with the diameter axis, we must look for a more appropriate index of stand density.

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SEARCH FOR A LIMITING DENSITY: REASONS AND APPROACH

Boris Zeide[1]

ABSTRACT. Forest science and management relies on standards of density such as full stocking. When determined analytically instead of empirically, a density standard would allow us to obtain more accurate estimates of actual and optimal stand density, stocking, site quality, self-thinning rate, and degree of disturbance. The analytical derivation of the standard, referred to as limiting density, involves the binomial model based on the duality of existing and missing trees.

INTRODUCTION

Modelling and prediction of forest growth would be impossible without the concept of stand density which is still not clearly understood. This lack of clarity is reflected in a bewildering variety of definitions, measures, indices, ratios, and charts used for estimation of density. The present contribution attempts to clarify this concept and to focus attention on determining limiting density which is the key to the understanding of density and several related concepts.

WHAT IS STAND DENSITY?

We all have some intuitive feeling of what stand density is. Without any measurements, we can easily tell a dense stand from a thinned or sparse one. Based on this feeling, no one would consider a stand with 100 trees per acre of the average diameter of 20 inches as equal in density to a stand with the same number of trees having the average diameter of 2 inches. The first is a good fully stocked stand while the second is not really a stand at all. Yet, according to the most authoritative sources (Ford-Robertson 1971, Wenger 1984), these stands have identical density, measured by the number of trees, although different stocking. These definitions contradict the meaning of the terms "dense" and "density". Another inconsistency of the accepted definitions is that they allow, in addition to number of trees, the use of several other variables (basal area or stand volume) as measures of density. Depending on which of these variables is used, quite different estimates of density could be obtained. Also, if density is nothing more than number of trees or basal area, it would be superfluous and confusing to use two terms for one concept.

Density means for us both size and number of trees taken together. Therefore, in practice density is most often expressed in terms of basal area which is a function of these variables. Stocking, then, is

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the ratio of density to some standard, a synonym of a relative density. Stands with identical density cannot have different stocking. We can use this conclusion to reject basal area (even though its ingredients might be right) as a measure of stand density because it is known that the same basal area can be found in stands of different stocking.

When we are talking about density, we have in mind nothing more than a certain combination, or function, of average size of trees and their number. If we are able to determine this function, it should be taken not as a measure or index of density but simply as density itself. To be more useful, the definition of stand density should specify the variables and form of the function as well as a method to find its coefficients. One of the two variables, number of trees per unit area, is clearly defined. The problem is to find a tree dimension that would best describe both its overall size and the occupied area.

WHICH IS THE BEST TREE SIZE INDICATOR?

Neither average crown projection or the crown width, which is the best predictor of the area occupied by an average tree and, consequently, of number of trees in closed stands, nor average tree mass, which is the most encompassing and natural indicator of tree size, satisfies this double requirement. Crown dimensions are often poorly related to the size of stem which is the largest component of tree mass. For the same reason, average tree mass is not a good predictor of number of trees. Mass increases with both stem diameter and tree height, while crowns increase with diameter of stems but, given trees of the same diameter, decrease with tree height. This fact of tree morphology has been often documented when crown dimensions were regressed separately on both diameter and height (Briegleb 1952, Harding and Grigal 1985). It can be explained by mechanical constraints, in particular by Euler's formula, in which a critical load atop a stable column must be proportional to the fourth power of the diameter of the column and inversely proportional to the square of its length. Both crown width and tree mass have technical disadvantages as well. Due to the irregular form and overlap of crowns, their average width cannot be reliably measured in closed stands. Measuring tree mass is not easier: it is notoriously time-consuming and error-prone work.

Stem diameter, the easiest tree dimension to measure, is a dependable predictor of both tree mass and crown dimensions. Because the diameter has a closer relationship to crown size than does the tree mass or stem volume, the Reineke (1933) equation is more accurate than the 3/2 power law of self-thinning of Yoda et al. (1963). Nevertheless, average diameter cannot be used for predicting the number of trees as was done by Reineke. His equation is statistically invalid because the average diameter (the independent variable) is computed using the number of trees (the dependent variable). This makes some of the statistics inaccurate (Weller 1987). These statistics include the slope of the equation when it is calculated using the reduced major axis technique.

The possibility of using more than one variable as an indicator of tree size has not lived up to expectations in preliminary trials. In addition to the collinearity problem, the multiple regression of crown mass on diameter and height, for example, was not statistically more accurate than a simple regression on the diameter alone (Zeide 1986).

So far the problem of the tree size indicator remains unsolved. A relationship between the average diameter and the average ground area per tree on plots of variable area with a fixed number of trees is currently being investigated. Unlike Reineke's, this relationship is statistically sound because its variables are obtained independently.

FORM OF THE FUNCTION

In completely closed stands number of trees should be functionally related to average crown projection and average crown diameter. In such stands the relationship between size and number of trees is equivalent to an allometric relationship between an indicator of size and crown diameter. As is known, an elementary power function describes well such allometric relationships. Both the Reineke equation and the law of self-thinning are power functions. Therefore, number of trees in completely closed stands, N, can be presented as a power function of average tree size, S. Its linear form is

$$\ln(N) = a - b\cdot\ln(S) \qquad (1)$$

where a and b are positive coefficients and ln is the natural logarithm function.

In closed stands the coefficients a and b as well as density do not change with age. The coefficient b would remain the same even if density decreased at random. The coefficient a, however, would decrease in this case. This coefficient satisfies our requirements to the definition of density: it is a function of size and number of trees that changes with density. Therefore, the coefficient a can be assumed as a definition of density:

$$\text{Density} = a = \ln(N) + b\cdot\ln(S) \qquad (2)$$

Although other expressions of density in terms of size and number of trees are possible, the logarithmic form makes the numbers more manageable, and calculations easier and more accurate because of the homogenized variance.

Density of real stands is constantly changing. It increases as trees grow and decreases when they die. These opposing factors are not synchronous: a gap created by the fall of a tree cannot be closed immediately. Due to this inevitable delay, all real stands are disturbed to some degree, their crown closure is never complete, and stocking is never full. A power function ceases to be applicable even to relatively undisturbed stands with intensive self-thinning as was shown for the 3/2 power law (Zeide 1987). Accumulation of gaps with age affects the accuracy of the Reineke equation as well. Although its deviation from linearity (on the lon-log scale) is less pronounced than that of the law, it is evident in many cases, especially those involving a wide range of sizes as, for example, Meyer (1938) discovered in his study of ponderosa pine (Pinus ponderosa Dougl.). A difference in gap accumulation might also explain why the slope of the Reineke equation is typically steeper for stands of intolerant species which tend to open earlier than for stands of more tolerant species.

There would be nothing wrong with a curved line if its equation were known. Unfortunately, it is not. The curvature varies with all the factors affecting density, and its quantification would require ad hoc models limited to particular species, site, and area. Now when the adequacy of both general models relating size and number of trees (the Reineke equation and the self-thinning law) is questioned, the choice is between dissolving the generality of the equation form into many local models, which have to be constructed over and over again for each particular situation, and preserving or enhancing the generality by some reformulation of the problem.

COEFFICIENTS OF THE FUNCTION

Given the slope (coefficient b), the coefficient a, or stand density, can be determined for any stand from measurements of size and number of trees. The slope, however, should be found using the stands of limiting density in which average tree size is independent of site quality. In actual stands the gap dynamics and the change in site quality with average tree size preclude the applicability of a power function, and the slope becomes meaningless.

LIMITING DENSITY

Those ideal stands of limiting density and a perfect relationship between size and number of trees do not exist in nature. The problem, therefore, is to find a method to extrapolate variables of any ordinary stand to their potential level, the level of a hypothetical stand of the same age that completely utilizes available resources of a given site. In particular, we are concerned with the potential level of stand density, limiting density.

Limiting density is not to be confused with density of stands variously known as normal, closed, undisturbed, fully stocked, fully occupied, and average best. The latest synonym, a by-product of the vogue for the 3/2 power law, seems to be "average maximum competition" stands (USDA 1985). These stands are intended to serve as standards or reference levels of density. There are several objections against using such a type of standard. First, there are no objective criteria to rule that a fully stocked stand is indeed maximally dense, that it is impossible to find an even more fully stocked stand. All these terms refer to stands that can actually be found in nature. Therefore, such stands, however dense they might be, are disturbed to some unknown degree. The second objection is that it is virtually impossible to prove that the site quality of the fully stocked stands and the studied one is identical. Because the reference level is determined by site quality, it makes no sense to impose the same density standard on stands occupying sites that differ in quality. This objection is particularly strong when a reference level is determined for the entire forest type (as recommended by the USDA (1985)) which encompasses a wide range of site quality. Unlike the concept of normality which implies that maximum growth occurs in maximally dense stands, limiting density is intended to provide only a reference level of density and not a goal for management. This distinction is necessary because actually the maximum productivity does not correspond to the maximum production.

REASONS

The main reason for introducing the notion of limiting density is to separate the processes that maintain stand density from those of gap formation, the effect of productive and predictable factors (genetics, site quality) from destructive and accidental forces (disturbances). In reality all these forces act together and cannot be physically separated. Limiting density can be grasped only by transcending reality or, in more technical terms, by the extrapolation of a suitable variable. The fact that limiting density cannot be determined experimentally is not a fault; this notion is useful precisely because it is imaginary. Only in stands of limiting density can we be sure about the form of a function relating size and number of trees. Conceptually similar imaginary separations have proved to be fruitful in other branches of science. In fact, contemporary science can be traced to a thought experiment in which the effect of inertia was separated from that of friction. Although nobody in any actual experiment could make bodies move indefinitely being pushed once, just those fictitious bodies are largely responsible for much of the quite real movement in our civilization.

All other practical advantages follow from this conceptual one. In addition to density estimation, limiting density is required to calculate stocking, or relative density: stocking is the ratio of the actual density to the limiting one. When the average size of trees in the hypothetical stand is set equal to the size of an actual stand, stocking is the ratio of the numbers of trees in these stands. Stocking of stands of limiting density is a unique maximum of density. It should not be confused with various optimal stocking levels which depend on a particular managerial situation.

At limiting density tree growth is impossible without a certain reduction in the number of trees, mortality. Due to this restriction, optimal stocking levels and, in particular, the density of maximum biomass growth is less than the limiting density. The fact that silvicultural thinnings cannot increase stand productivity indicates that this optimal density is pretty close to the average maximum observed density of forest stands. Although limiting density is not optimal and cannot be used as a management goal, it is the best reference level of density. Among other advantages of this reference level is that it is functionally related to optimal density. As a result, optimal density could be determined from the limiting one without tedious and time-consuming increment investigations.

Knowledge of optimal density leads to estimation of site quality where a major problem is to eliminate the effect of stocking variability.

Because actual stand volume varies with stocking, we do not use it as a site indicator while we do use the height of dominant trees which is less sensitive to variations in stocking. The height, however, is an indirect and not altogether reliable indicator of site. Optimal density is an attractive alternative because this direct indicator of stand productivity is not affected by stocking variability. When optimal density is known, optimal biomass (which is another function of the same size and number of trees) can be easily obtained. The maximum of its mean increment characterizes site quality.

The relationship between size of trees and their number is affected simultaneously by both a mutually adjusted change of these variables (self-thinning) and disturbance. Studies of either process will remain on shaky ground unless we are able to analyze them separately. The knowledge of limiting density will provide a sound quantitative basis for investigation of these processes.

To sum up, the extrapolation of density to its limiting level linearizes (on the log-log scale) the relationship between average size of trees and their number and allows us to obtain more accurate estimates of actual and optimal stand density, stocking, site quality, self-thinning rate, and degree of disturbance.

APPROACH

The key premise of the proposed approach is that there is an upper limit to density and the values of other stand variables. In order to overcome the discussed objections against the notions of normality or full stocking, we need a practical method that is capable of producing the potential values of a given stand within the stand itself. The same limit might well be common to many stands similar in type and site quality so that the density would actually have to be determined for only a few of them. Limiting density could be reconstructed by many different methods. Below is a tentative description of one of them based on the most fundamental distribution in nature, the binomial distribution.

Consider a set of plots established within a given stand. If the average sizes of trees on each of the plots were equal, we could use the number of trees per unit area of a plot as the expression of density of the plot. If the sizes differ, we can adjust the numbers to the common (for example, stand average) size assuming that on the log-log scale the relationship between the size and the number is linear. Adjusted numbers are not affected by the variability in site quality among the plots established within a stand, and their upper limit corresponds to the average site quality of the stand. In any self-thinning stand, the adjusted numbers converge to a certain maximum number, N, which represents the potential number of trees that would be present in a truly undisturbed stand completely utilizing the site's resources. This number, common to all the plots within a stand, is the sum of the adjusted numbers of existing and missing trees on each plot. The maximum number can be determined using simple probabilistic reasoning.

Consider a pool (an analog of a stand) containing a large number of green, g, (existing trees) and transparent, t, (missing trees) balls mixed in, say, the ratio of 3 to 1. This means that the probabilities of green and transparent balls are 0.75 and 0.25 or, more generally, p and q, respectively. The balls are taken out of the pool with a scoop containing four balls of either color. This corresponds to the maximum number and satisfies our assumption that the number of existing trees (or green balls) per unit area of a plot cannot exceed a certain quantity. The probability to get a g-t-t-t sample or any other sample with one green ball is 0.75·0.25·0.25·0.25. The number of combinations in which one green ball can appear (g-t-t-t, t-g-t-t, t-t-g-t, t-t-t-g) is equal to $4!/(1!3!) = 4$. The probability, $P(1)$, of a sample with one green ball and three transparent balls appearing in any order is

$$P(1) = (4!/(1!3!))0.75(0.25)^3.$$

Similar considerations lead to

$$P(2) = (4!/(2!2!))(0.75)^2(0.25)^2$$

and, generally, to the binomial distribution

$$P(K) = (N!/(K!(N-K)!))(p)^K(q)^{N-K} \tag{3}$$

where K ($0 \leq K \leq N$) is the number of green balls (or the adjusted number of existing trees). The distribution can be further generalized for a continuous case.

Equation (3) contains only one unknown variable, N, (not P(K)) because $q = 1 - p$ and $p = \bar{K}/N$ where $\bar{K}$ is the average adjusted numbers of the plots which is simply the average number of trees per unit area. The proper average in this case is neither arithmetic nor quadratic mean (Zeide 1983). The potential number of trees can be found by minimizing the difference between the actual and predicted (equation (3)) probabilities. This potential number also corresponds to the maximum of the following sum:

$$\sum_{K=\min}^{\max} (N!/(K!(N-K)!))(p)^K(q)^{N-K} \tag{4}$$

When average sizes of trees, S_i, and their potential numbers, N_i, are known for each stand i in a group of stands, we can calculate the coefficients a and b of equation (1). Then for each stand we obtain

density = $\ln(\bar{K}_i) + b \ln(S_i)$;
stocking = $\bar{K}_i/N_i$;
limiting density = $\ln(N_i) + b \ln(S_i)$;
site quality = maximum of (optimal biomass/age);
relative rate of self-thinning = b;
degree of disturbance = $(\ln(N_i) - \ln(\bar{K}_i))/\ln(N_i)$.

These definitions could provide a new level of consistency and accuracy in the description of forest stands.

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FOREST GROWTH MODELS:
PARAMETER ESTIMATION USING REAL GROWTH SERIES

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ABSTRACT. Two previously published basal area projection models (referred to as Souter's model and Pienaar's model) were fitted to three data set structures formed from a real growth series: 1) nonoverlapping growth intervals (NI), 2) all possible growth intervals (AI) and 3) longest growth interval only (LI). No autocorrelation was present for either the LI or NI data structures while the large autocorrelations found in the AI data structure were accounted for in the fitting process. Comparisons of model forms fitted with the three data structures showed: 1) Souter's model performed consistently better than Pienaar's model; 2) the AI data structure was not the superior structure for either model form; 3) the best data structure was model form dependent with the NI structure best for Souter's model and the LI structure best for Pienaar's model.

INTRODUCTION

Data resulting from remeasured permanent plots or trees was referred to as a "real growth series" by Turnbull (1962). Today, real growth series data are available for many tree species in many locations throughout the world. Such real growth series data have been used extensively for investigating tree and stand dynamics as well as for modeling growth. An often used growth modeling formulation was developed by Clutter (1963) and has subsequently been referred to as the algebraic difference method (ADM) (Borders and others, 1984; Ramirez and others, 1987). In general, an algebraic difference equation (ADE) has the form

$$Y_2 = f\ (Y_1, A_2, A_1)$$

where Y_2 is the value of a continuous variable defined on a tree or stand at time 2, Y_1 is the same variable's value at time 1; A_2 and A_1 are the tree or stand ages at times 2 and 1.

Obviously, real growth series data can be used in fitting routines to obtain sample estimates of population parameters for ADE's. However, what is not obvious is which growth intervals should be used to obtain the parameter estimates. For a situation in which the unit of interest (tree or plot) has been measured at only two ages, say A_1 and A_2, the question is moot, obviously the only growth interval is from A_1 to A_2.

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However, if the unit under study has been measured 3 or more times, the issue becomes more complex. For example, if we have a real growth series for a set of units each measured at ages A_1, A_2, A_3, ..., A_n, there are $\binom{n}{2}$ possible growth intervals that can be formed. That is A_1 to A_2, A_1 to A_3, ..., A_1 to A_n, A_2 to A_3, etc.... The most common procedure for estimating parameters in ADE's is to use only the nonoverlapping growth intervals (i.e. A_1 to A_2, A_2 to A_3, ..., A_{n-1} to A_n) (Borders and others, 1984; Clutter, 1963; Sullivan and Clutter, 1972). Another possibility is to use only the longest interval for each unit (i.e. A_1 to A_n). Once an ADE has been fitted, it can be used to make projections for any number of years (i.e. any number of growth intervals). Thus, we were prompted to question the use of only nonoverlapping growth intervals in the parameter estimation phase of model development. Intuitively we are led to ask if all the growth information available in a real growth series is extracted when either the NI or LI structure is used. Our objective is to compare and contrast the following three data set formulations:

1) Nonoverlapping growth intervals (NI),
2) All possible growth intervals (AI),
3) Longest growth interval (LI),

and their impact on estimation with two previously published basal area growth model forms derived using the ADM.

MODELS

We refer to the following basal area growth model from the work of Pienaar and Shiver (1986) as Pienaar's model:

$$\ln B_2 = \ln B_1 + \beta_1(1/A_2 - 1/A_1) + \beta_2(\ln N_2 - \ln N_1) + \beta_3(\ln H_2 - \ln H_1) + \beta_4(\ln H_2/A_2 - \ln H_1/A_1) \qquad (1)$$

In (1), B_i, N_i and H_i are basal area per acre, number of trees per acre, and dominant height at age A_i. The letters 'ln' denote natural logarithm and β_1, β_2, β_3, β_4, are parameters to be estimated.

The following basal area growth model was found to fit well for natural stands of loblolly pine (pinus taeda) by Souter (1986) and thus we call it Souter's model.

$$\ln B_2 = (A_1/A_2)\ln(B_1) + \beta_1(1 - A_1/A_2) + \beta_3 S(1 - A_1/A_2) + \beta_3[\ln N_2 - (A_1/A_2)\ln N_1]\ , \qquad (2)$$

where S is base age 50 site index. In our study, S denotes base age 25 site index. Both models were transformed by subtracting the first term on the right from both sides so that linear least squares (zero intercept) could be used to estimate the parameters.

Several authors have investigated the effects of autocorrelation on parameter estimation in forest growth and yield models (Swindel, 1968; Sullivan and Clutter, 1972; Elston and Grizzle, 1962). Without exception, they conclude that ordinary least squares (OLS) estimators are adequate and it is not necessary to use more elaborate fitting procedures when faced with autocorrelations in real growth series data. However, these authors did not deal with the effect of correlations among residuals for the AI structure defined above. Thus, a fitting procedure based on the joint generalized least squares (JGLS) technique known as seemingly unrelated regression (SUR) (Zellner, 1962) was used to account for the correlations among residuals for the AI structure. In addition to OLS estimation with all three data structures, both model forms were fitted to the AI data using this JGLS technique.

DATA

The data for this investigation come from a Southeastern USA regionwide slash pine (*Pinus elliottii*, Engelm.) stand density study, which was established and measured by Union Camp Corporation and most recently analyzed by Borders (1984). The data consist of 63 different installations of slash pine study plots. At each installation, variable sized plots, each containing 50 trees, were planted at densities ranging from 100 to 1800 trees per acre (tpa). Each plot was initially measured at age 2 and then every 3 years thereafter with the oldest ages being 20. Only data from plots with 1100 or fewer stems and measurements at ages 5 and greater were used in this study. Additional details about the data are provided by Borders (1984).

If a plot was measured at ages 5, 8, 11 and 14, the LI data is from age 5 to 14, the NI data from age 5 to 8, 8 to 11 and 11 to 14, and the AI data are from ages 5 to 8, 5 to 11, 5 to 14, 8 to 11, 8 to 14 and 11 to 14.

RESULTS

Both models were fit to each data set formulation. The signs and magnitude of all parameter estimates were the same with the exception of the β_1 parameter in Souter's model (Tables 1, 2). After fitting these models to the three data sets, residuals were examined for autocorrelation. As expected, no autocorrelation occurred with the LI data. No autocorrelation was present for the NI data for either model. Conversely, very high autocorrelation was found to exist among residuals for the AI data for both model forms. JGLS parameter estimates for the Pienaar model were similar to the ordinary least squares (OLS) fits (Table 1). However, for Souter's model the JGLS parameter estimates were quite different from those based on OLS (Table 2).

To evaluate the goodness of the two model forms fitted with each data structure, they were used to project basal area for a validation data set. This data set consisted of a representative sample of 20 percent of the study plots which were not used to estimate parameters.

Table 1. Parameter estimates for Pienaar's model by data structure and estimation method.

Data (Estimation)	Parameter β_1	 β_2	 β_3	 β_4
	------------------	estimates	------------------	
LI (OLS)	-12.638	0.650	1.640	5.642
NI (OLS)	-12.162	0.718	1.467	4.302
AI (OLS)	-11.567	0.683	1.612	4.813
AI(JGLS)	-11.767	0.812	1.468	3.816

Table 2. Parameter estimates for Souter's model by data structure and estimation method.

Data (Estimation)	Parameter β_1	 β_2	 β_3
	---------------	estimate	---------------
LI (OLS)	0.538	0.019	0.652
NI (OLS)	0.502	0.018	0.652
AI (OLS)	0.078	0.023	0.687
AI(JGLS)	3.401	0.019	0.132

Residuals were calculated for all possible growth projections in this data for both model forms fitted to each data set formulation and for the AI data set fit with the JGLS technique.

Souter's model was consistently superior to Pienaar's model for projecting basal area in the validation data (Table 3, 4). It should be noted that observed dominant heights and trees per acre were used in the projections to avoid problems associated with contemporaneous correlations commonly found among regression equations for different stand characteristics (Borders and Bailey, 1986). Both models exhibited decreasing precision and explained less observed variation as the projection period increased (Tables 3, 4). Furthermore, both models performed better for a given projection length as initial age increased.

The AI data structure was not the superior structure for either model form (Tables 3, 4). Souter's model performed consistently better when fitted with the NI data structure (Table 3) while Pienaar's model was consistently better when fitted with the LI data structure (Table 4).

TABLE 3. Statistics of fit for Souter's model by data structure, estimation method and projection age (the asterisk indicates the best performance among the four alternatives for a given projection age).

Initial Age	Data (Estimation)	Projection Age 8 D[1]	Projection Age 8 PVE[2]	11 D	11 PVE	14 D	14 PVE	17 D	17 PVE	20 D	20 PVE
5	AI(OLS)	-2.5	89.3	-3.8	82.6	-5.2	76.8	-3.0	80.6	-1.0	92.6
	AI(JGLS)	0.7*	93.3*	1.8*	86.5	0.7*	79.6	-0.7*	60.2	-2.2	44.6
	NI(OLS)	-1.9	92.0	-2.6	87.7*	-3.6	84.1*	-2.0	84.5*	-0.6*	92.9*
	LI(OLS)	-2.0	91.7	-2.9	87.0	-4.2	83.2	-2.7	83.7	-1.3	92.5
8	AI(OLS)	-	-	-0.6	95.4	-2.2	88.8	-0.5	87.9	-1.5	94.8
	AI(JGLS)	-	-	1.5	95.3	0.6*	88.7	0.2	72.8	-2.0	62.0
	NI(OLS)	-	-	-0.1*	96.3*	-1.3	91.6*	0.0*	89.5*	-1.4*	95.3*
	LI(OLS)	-	-	-0.2	96.2	-1.7	91.2	-0.4	89.3	-1.9	94.9
11	AI(OLS)	-	-	-	-	-2.1	96.6	-1.8	93.3	-1.3	97.3
	AI(JGLS)	-	-	-	-	-1.0*	96.0	-1.9	86.0	-1.9	78.5
	NI(OLS)	-	-	-	-	-1.7	97.3*	-1.5*	94.5*	-1.2*	97.8*
	LI(OLS)	-	-	-	-	-1.9	97.1	-1.8	94.2	-1.6	97.5
14	AI(OLS)	-	-	-	-	-	-	-0.5	97.5	-2.6*	97.7
	AI(JGLS)	-	-	-	-	-	-	-1.2	95.0	-4.3	87.5
	NI(OLS)	-	-	-	-	-	-	-0.3*	97.8*	-2.6*	98.1*
	LI(OLS)	-	-	-	-	-	-	-0.5	97.8*	-2.9	97.9
17	AI(OLS)	-	-	-	-	-	-	-	-	0.2	99.2
	AI(JGLS)	-	-	-	-	-	-	-	-	-2.2	93.1
	NI(OLS)	-	-	-	-	-	-	-	-	0.1*	99.3*
	LI(OLS)	-	-	-	-	-	-	-	-	-0.1*	99.2

[1] D = Average observed minus predicted basal area ($ft^2/acre$)

[2] PVE = percent variation explained

$$= 100 \{1 - [\sum_i (BA_i - BA_i)^2]/[\sum_i (BA_i - \overline{BA})^2]\}$$

TABLE 4. Statistics of fit for Pienaar's model by data structure, estimation method and projection age (the asterisk indicates the best performance among the four alternatives for a given projection age).

Initial Age	Data (Estimation)	Projection Age									
		8		11		14		17		20	
		D[1]	PVE[2]	D	PVE	D	PVE	D	PVE	D	PVE
5	AI((OS)	-3.3*	82.3	-5.9*	69.4	-9.8	45.1	-11.2	6.6	-10.6	47.8
	AI(JGLS)	-4.2	76.4	-8.1	56.5	-12.7	25.0	-12.9	0	-10.6	47.4
	NI(OLS)	-3.6	80.1	-6.3	65.5	-9.9	42.0	-10.0*	13.8*	-7.9*	58.3*
	LI(OLS)	-3.6	82.4*	-5.9*	70.9*	-9.5*	46.0*	-11.3	1.5	-11.4	44.6
8	AI(OLS)	-	-	-0.5	94.9	-2.6	92.1	-3.1	84.1	-7.0	77.5
	AI(JGLS)	-	-	-1.2	94.3	-3.9	88.3	-4.3	79.3	-7.7	74.9
	NI(OLS)	-	-	-0.5	94.9	-2.5	91.2	-2.4	84.6	-5.5	80.6
	LI(OLS)	-	-	0.0*	95.1*	-1.4*	93.9*	-1.6*	87.0*	-5.2*	81.1*
11	AI(OLS)	-	-	-	-	-1.7	95.8	-3.5	88.5	-3.0	93.0
	AI(JGLS)	-	-	-	-	-2.3	95.9	-4.2	86.9	-3.6	92.9
	NI(OLS)	-	-	-	-	-1.7	96.3*	-3.1	89.5	-2.3	94.1*
	LI(OLS)	-	-	-	-	-1.0*	95.8	-2.2*	90.1*	-1.4*	93.9
14	AI(OLS)	-	-	-	-	-	-	-1.4	96.3	-4.3	94.1
	AI(JGLS)	-	-	-	-	-	-	-1.5	96.2	-4.3	95.3*
	NI(OLS)	-	-	-	-	-	-	-1.2	96.6	-3.8	95.2
	LI(OLS)	-	-	-	-	-	-	-0.9*	96.7*	-3.4*	94.5
17	AI(OLS)	-	-	-	-	-	-	-	-	0.3*	95.5
	AI(JGLS)	-	-	-	-	-	-	-	-	0.7	97.4*
	NI(OLS)	-	-	-	-	-	-	-	-	0.6	96.4
	LI(OLS)	-	-	-	-	-	-	-	-	0.6	94.8

[1] D = Average observed minus predicted basal area (ft^2/acre)

[2] PVE = percent variation explained

$$= 100 \{1 - [\sum_i (BA_i - BA_i)^2]/[\sum_i (BA_i - \overline{BA})^2]\}$$

DISCUSSION

Intuitively, it seems that an algebraic difference model form fitted using all possible growth intervals may be superior for projecting for any number of years than when the model is fitted using only nonoverlapping or longest growth intervals. This was clearly not the case in this study. We found that differences in projection ability by data structure was model form dependent. Souter's model performed best when fitted with the NI structure while Pienaar's model performed best when fitted with the LI structure.

No autocorrelation was found in the NI data structure but was present in the AI data structure. It is interesting to note that accounting for these autocorrelations in the fitting process improved the projection ability of Souter's model but not Pienaar's model. This indicates that problems associated with autocorrelation may also be model form dependent.

In this type of empirically based study it is not possible to ascertain biasedness and efficiencies of parameter estimates obtained with the various data structures and estimation methods. Theoretical study is needed to quantify such properties as well as to investigate the empirical results presented above.

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EXPERIENCE WITH AN ADVANCED GROWTH MODELLING METHODOLOGY

Oscar García[1]

ABSTRACT. A number of stand growth models have been developed in New Zealand using relatively sophisticated mathematical and statistical techniques. The models consist of a system of stochastic differential equations, and the parameters are simultaneously estimated by maximum likelihood. Five models have been completed and another two are under development.

INTRODUCTION

A series of stand growth models covering the main commercial forests and forest regions of New Zealand is being completed. A general methodology was developed to facilitate the production and updating of these models.

I give in the next section some background information on characteristics of New Zealand forestry that have influenced our approach. Then the methods and results obtained are briefly described.

More detailed accounts of the methodology have been given by García (1979, 1983, 1984). For other growth modelling efforts in New Zealand see Goulding (1986) and Tennent (1982).

THE FORESTRY CONTEXT

New Zealand has practiced plantation forestry for almost a century. A combination of diminishing native forest resources and pressure from conservation groups has accelerated a shift to man-made production forests. By 1955, wood production from plantations equalled that from the native forests. There are now 1.1 million hectares of plantations, accounting for 95% of the annual production of 10 million cubic meters.

The most successful species has been radiata pine (Pinus radiata D. Don), of which there are over 1 million hectares. In a distant second place comes Douglas fir (Pseudotsuga menziesii (Mirbel) Franco), at 61 thousand hectares. Radiata pine is the world's most extensively planted exotic softwood, and is characterized by fast growth and a versatile timber. Its predominance in New Zealand has resulted in considerable research effort directed at this species.

The concentration of planting activity in the 1920s and 1930s, and then again after 1960, produced a very uneven age-class distribution. The result is large changes in rotation age and supply conditions over

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time. After a period of abundance, we are currently in a comparatively tight timber supply situation, yet production is projected to double by the end of the century. Clearly, adequate planning under these circumstances requires accurate growth and yield forecasts.

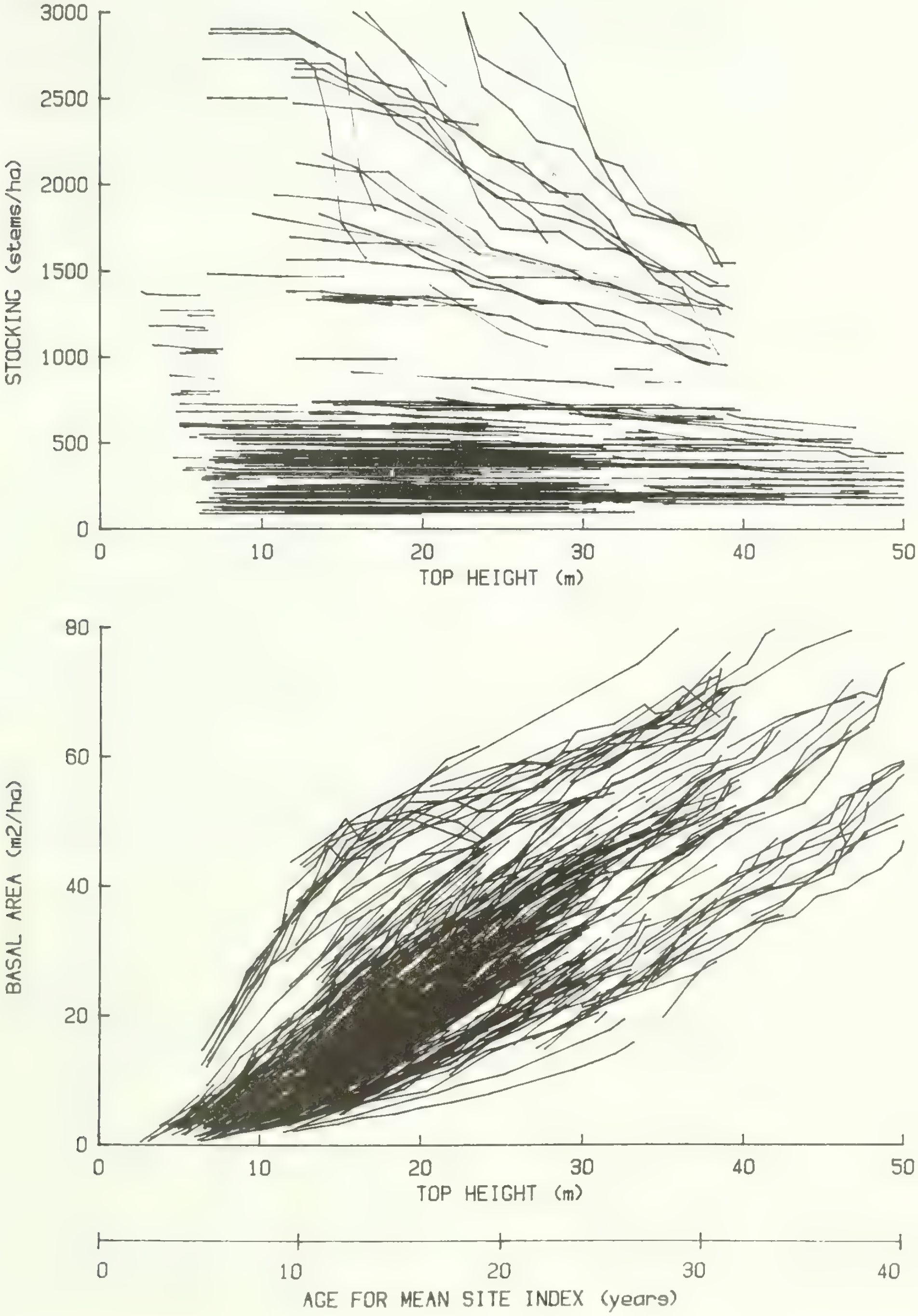

Figure 1. Permanent sample plot data for the Pumice Plateau model. Consecutive measurements between thinnings are joined by lines.

Another factor influencing growth modelling is the high silvical flexibility of radiata pine, and the variety and intensity of silvicultural treatments applied in its management. Figure 1 gives some idea of the range of stockings which currently exist as a result of varying initial spacings and thinning regimes. In the past two decades, silviculturalists have constantly pushed models and data to their limits, by repeatedly advocating lower stocking regimes than were previously considered practicable. Experimentation and data collection has ensured that there is now, at least for some regions, a reasonable data base on the response to the various growing conditions. A recent resurgence of interest in less intensive management emphasizes the importance of sampling and modelling the full range of growing conditions, avoiding the temptation to focus exclusively on current practices.

Although the idea of having one growth model applicable to the whole country is attractive on philosophical grounds, practical considerations indicated the necessity of developing regional models. It was known that there existed important differences, not just in growth rates, but also in growth patterns between regions. For example, there are differences in the shape of site index curves (Burkhart and Tennent, 1977), and radiata pine in Southland produces higher basal areas for a given height than in the central North Island. Other interregional differences in growth patterns have since been found, and are discussed below. Current knowledge is insufficient to allow the parameterization of these differences by continuous environmental variables; only stratification into discrete regions is possible. In addition, with over 7000 permanent sample plots for radiata pine in New Zealand, it was necessary to subdivide the work into more manageable portions. The main radiata pine forests were tentatively classified into 8 groups for growth modelling purposes, based on climate, geology, soils, and availability of data. Once the first set of models for the country is obtained, it will then be possible to assess the desirability of pooling regional data sets.

METHODOLOGY

THE STATE SPACE APPROACH

The growth models are stand-level models, with the state of a stand at any point in time described by a small number of summary variables. These state variables include the net stand basal area, number of stems per hectare, and top height. Some of the models use additional variables representing the degree of canopy closure and/or nutrient levels. Such information is easily obtained by forest managers, and is sufficient for growth prediction in most instances. Other information of interest, such as volumes for various products, or diameter distributions, can be estimated from the values of the state variables. The rates of change of the state between treatments (thinnings, pruning, fertilizing) are modelled by a system of differential equations.

The principles may be explained with the three-dimensional state space depicted in Figure 2. This is a stereoscopic pair in which measurements from permanent sample plots are shown as points in a space defined by three state variables, basal area, average spacing and top height. Consecutive measurements between thinnings are joined by lines. The basic assumption is that the current location of a stand in this space, plus any subsequent thinnings, completely determine its future development independently of its past history. For any dynamic system, this can always be made true by using a sufficiently detailed state description. An appropriate state description must also allow other required information to be estimated. For example, the stand volume might be estimated by a function of basal area and top height. The slopes of the trajectories at any point in the state space are modelled by differential equations. By integration, the state at any future time can be calculated as a function of the current state. Thinnings cause instantaneous jumps in the state space.

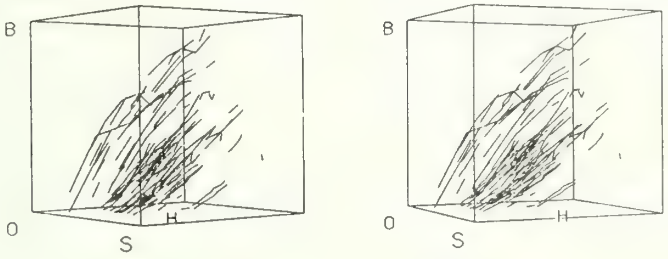

Figure 2. Stereogram showing the Golden Downs data in a three-dimensional state space. B=basal area (0-100 m^2/ha), S=average spacing (0-10 m), H=top height (0-50 m).

Incidentally, it can be seen in Figure 2 that the data tend to be concentrated near a surface in the three-dimensional space. A similar effect was noted by Decourt (1974), and may explain why models using two-dimensional state spaces (basal area and height, or basal area and age) often perform reasonably well. We have found, however, substantial improvements in prediction by introducing a third variable.

GROWTH EQUATIONS

The differential equations used can be seen as a multivariate generalization of the Bertalanffy-Richards model. The univariate version of this model, widely used for site index curves, can be written as a linear differential equation with a power transformation of the state variable H, e.g. top height:

$$dH^c/dt = a H^c + b \; . \tag{1}$$

Some of the parameters a, b or c are usually functions of the site index. For a three-dimensional state vector, for example (B,N,H) consisting of basal area, number of stems per hectare and top height, we use three linear differential equations with power transformations of the form

$$B^{c1}N^{c2}H^{c3} \; . \tag{2}$$

In general, using standard matrix notation, for an n-dimensional state vector $\underline{x}$ the multivariate version is

$$d\underline{x}^{C}/dt = A\ \underline{x}^{C} + \underline{b} \;, \tag{3}$$

with $\underline{x}^{C}$ defined as

$$\underline{x}^{C} = \exp\ [\ C \ln \underline{x}\ ],$$

and A, C and $\underline{b}$ being n-dimensional matrices and vectors of parameters.

Notice that many mensurational variables, such as mean diameter, average spacing, and volume estimated by logarithmic volume equations, are of the form (2). Therefore, use of these alternative variables instead of B, N or H would also result in a model of the form (3).

The models developed to date have used three to five state variables, with the site index entering into the equations in various ways. Versions with different subsets of the components of A, $\underline{b}$ and C fixed at zero have been tried. Extensions of (3), where the right-hand-side is multiplied by functions of time or of some of the state variables, have also been used. Some of these variations are discussed in the RESULTS section.

In this approach the fundamental data units are pairs of consecutive measurements. Therefore, the availability of permanent sample plots remeasured over a long period of time, although desirable, is not essential. This makes these methods particularly interesting for situations where long-term experimental data is not available.

ESTIMATION

One of the components of (3) is always of the form (1), representing the height growth and site index curves. The parameters for this equation are estimated first. A stochastic process representing the environmental variation in growth conditions is added to the right-hand-side, and a random variable representing measurement errors is also included. While some of the parameters are common to all plots, others are specific to individual plots (site-dependent). An explicit expression for the likelihood function is obtained, and all the parameters are estimated simultaneously by a direct maximization of this function.

Once the height growth parameters and the site indices for all plots have been estimated, the rest of the parameters in (3) are estimated by a similar procedure. A stochastic process is added to the right-hand-side of (3), but measurement errors are not directly modelled.

Here, after introducing functional dependencies on the site index, the parameters to be estimated are common to all plots. The likelihood function can then be maximized with a general-purpose optimization procedure.

For each region, a number of variations of the general model have been tried, and extensive validation and graphical examination of the residuals has been carried out.

RESULTS

Some information on the models that have been produced, all for radiata pine, is given in the following table.

TABLE 1. Growth models developed with this methodology.

Model	Date finished	Measurement pairs	Sample plots
Golden Downs	1981	339	119
Southland	1982	171	56
Hawkes Bay	1983	634	207
North Island Sands	1984	1100	513
Auckland Clays	1987	510	228
Pumice Plateau	-	2295	297

Most of the work on these models was done by M.E. Lawrence (Southland, Hawkes Bay, Pumice Plateau), A.G. Dunningham (N.I. Sands, Pumice Plateau), and R.G. Shula (Auckland Clays).

The Golden Downs model is the only one that has been formally published to-date (García, 1984). The state variables are basal area, stems per hectare, and top height. Site index enters in a factor multiplying the right-hand-side of (3), i.e., its effect is a change in the time scale.

The Southland data set was used in the initial development of the methodology. Some preliminary results were reported by García (1979). In 1982 the parameters were re-estimated with the same relationships used for Golden Downs. This model is considered as provisional because not all the available data have been used, and only a few variations of the general model have been investigated.

For Hawkes Bay, a reduction in growth was detected immediately following heavy thinnings. A fourth state variable, representing a measure of relative site occupancy or canopy closure was included to account for this effect (García, 1984). Analysis of residuals also showed that the effect of site index on basal area increment was less pronounced than for height increments. A model with different site multipliers for the different equations in (3) accounted satisfactorily for this effect.

For the North Island Sands, no improvement was obtained by introducing a measure of canopy closure and a three-dimensional state vector was used, as for Golden Downs. The effect of site index for the N. I. Sands, however, is different from that in the other models. The site index curves were found to be anamorphic, i.e., instead of changing the time scale, the site index alters the asymptotes. A model that varies the asymptotes for all the state variables as a function of site index was found to be appropriate.

The Auckland Clays region includes soils with varying degrees of phosphorous deficiency. It is normal management practice to fertilize the forest plantations in this region. A model was developed based on data from plots that had been maintained at an adequate level of P (above 0.11% foliar P). This model also includes a canopy closure variable, as for Hawkes Bay. The site index affects the time scale, as for Golden Downs. Using data from fertilizer experiments, the model was modified to predict the effect of lower phosphorous levels. In this version the foliar P level is included as an fifth state variable, with an associated decay function describing its change over time. The additional variable is included in the other equations via multiplier functions, adjusting the growth in relation to that predicted for the adequately fertilized stands.

The most extensive data set was that for the Pumice Plateau (Figure 1). An interim model with a three-dimensional state vector has been produced, but has been found to overpredict slightly the growth following heavy thinning and pruning. Work is under way to account for these effects. In the other models, any effect of pruning on growth is confounded with other silvicultural treatments, and the lack of data prevents adjustments for it. The Pumice Plateau data, however, includes results from a number of silvicultural experiments and more pruning information. This information is being used through a canopy closure variable affected by both thinning and pruning. Unlike in the previous models, this fourth variable is likely to enter the growth equations in the form of multipliers, allowing for more consistent extrapolations.

Work has started on a radiata pine model for Canterbury. A feature of this model will be the use of data obtained from stem analysis in order to fill gaps in the data base. It is planned to complete an adequate first coverage of the main New Zealand exotic forests with a new model for radiata pine in Southland, and one or more models for Douglas fir.

CONCLUSIONS

The methodology described has proved to be feasible and effective, and has provided a consistent framework for the development of a series of growth models. Excellent predictions have been obtained over a wide range of treatments and growing conditions.

Currently, these methods can not be recommended for general use by the casual growth modeler; the capacity to understand the techniques, and to modify them if necessary, is essential. Also, computing costs may be higher than for some other methods. For those with an adequate level of expertise, however, the efficient use of the data makes this approach attractive. In most instances, the costs of growth model development are negligible in relation to the costs of data collection and the consequences of prediction errors.

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COMBINING INVENTORY DATA WITH MODEL PREDICTIONS

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ABSTRACT. Use of composite estimators which combine sample information with model predictions is discussed. It is recognized that the model prediction will often be biased. Nine new potential estimators are introduced for this case. The estimators are tested in a simulation. The data were generated from normal distributions with parameters chosen to be representative of values anticipated in yield prediction problems. Results indicate that when the bias is small, composite estimators which account for the possible bias of the model prediction yield a smaller squared error than the sample mean, but not as small as that obtained with the usual composite estimator that ignores bias. When the bias is large, the composite estimators which account for bias converge in squared error to the sample mean, while the squared error of the usual composite estimator becomes large. If the bias is in the range we expect, then accounting for bias is probably not necessary. However, if one is unsure of the bias or wishes to protect against large biases, a composite estimator which accounts for bias may be desirable. With one exception, there did not appear to be any reason to prefer one of the new estimators over the others.

INTRODUCTION

In usual forest inventories only field data collected in a stand are used to estimate parameters of interest for that stand. It seems intuitively obvious that historical field data and growth and yield models contain information that might be combined with the sample or field data to produce a more efficient estimator. In this study we examine methods for combining model predictions with sample data to produce a composite estimator.

The idea of combining sources of information is not new. Such procedures have long been used in sample surveys. In general, suppose we are interested in estimating some quantity, say $\mathbf{Y}$. Further suppose we have two estimators for $\mathbf{Y}$. We call these two estimators y_1 and y_2. If we measure an estimator's "goodness" by its mean square error (**MSE**), then it can be shown (e.g., see Schaible 1978) that the composite estimator

$$y_c = \mathbf{W}\, y_1 + (1-\mathbf{W})\, y_2 \qquad [1]$$

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is in general superior to either y_1 or y_2 when **W** is determined as follows:

$$\mathbf{W} = \frac{\mathbf{MSE}(y_2) - \mathrm{E}(y_1-\mathbf{Y})(y_2-\mathbf{Y})}{\mathbf{MSE}(y_1) + \mathbf{MSE}(y_2) - 2\mathrm{E}(y_1-\mathbf{Y})(y_2-\mathbf{Y})} \qquad [2]$$

where $\mathbf{MSE}(y_i)$ = mean square error of estimator y_i, and E denotes expected value. In application it is usually assumed that the components are unbiased and independent, so [2] reduces to:

$$\mathbf{W} = \mathbf{V}(y_2)/\{\mathbf{V}(y_1)+\mathbf{V}(y_2)\}, \qquad [3]$$

where $\mathbf{V}(y_i)$ = variance of estimator y_i. The exact sample variance of y_c is difficult to determine, but good approximations have been developed by Meier (1953) and Cochran and Carroll (1953).

FORESTRY APPLICATIONS OF COMPOSITE ESTIMATORS. Burk et al. (1981) and Green and Strawderman (1986) have used y_c to combine yield model predictions with sample data. In both cases. it was assumed that y_1 (the yield model prediction) and y_2 (the sample mean) were unbiased and independent. Expression [3] was used, and $\mathbf{V}(y_1)$ and $\mathbf{V}(y_2)$ were estimated by the prediction variance of the yield model and the squared sample standard error, respectively.

However, upon closer inspection, both the unbiasedness and independence assumptions are suspect. If a-priori stand averages are used as independent variables in the yield model, then the model prediction is a constant and the probability that it will equal the "true value" of the attribute of interest is zero. Thus the model prediction is biased. An example of such a case is a plantation with a known age and site quality and number of stems determined from a survival curve. If attributes measured on each plot are used as independent variables and predictions are obtained for each plot and then averaged, the model prediction is highly correlated with the sample mean. In this study we address the issue of bias of the yield model when a-priori stand averages are used as independent variables. We will assume throughout that y_1 and y_2 are independent.

The bias of yield model predictions has important implications for the use of composite estimators. Expression [3] is invalid because the MSE and variance of the yield model are not equivalent. If the independence assumption is tenable, expression [2] reduces to:

$$\mathbf{W} = \mathbf{V}(y_2) \;/\; \{\mathbf{MSE}(y_1) + \mathbf{V}(y_2)\} \qquad [4]$$

$$= \mathbf{V}(y_2) \;/\; \{\mathbf{V}(y_1) + \mathbf{V}(y_2) + \mathbf{B}^2\},$$

where $\mathbf{B} = \mathrm{E}(y_1) - \mathbf{Y}$ = the bias of the yield model. The problem thus becomes one of finding a new estimator for [4] which will minimize the **MSE** of y_c. Since y_1 is biased, y_c will be biased. However, if y_c has lower **MSE** then y_2, the bias must be negligible.

DEVELOPMENT OF NEW COMPOSITE ESTIMATORS. Note that while y_1 is biased, y_2 is not. An obvious procedure is to estimate $\mathbf{MSE}(y_1)$ by the sum of its variance and the squared difference between y_1 and y_2. The estimator is then derived by term by term substitution:

$$w_1 = v(y_2) \;/\; \{v(y_1) + b^2 + v(y_2)\}. \tag{5}$$

where w_1 is an estimate of $\mathbf{W}$, $v(y_i)$ is the estimated variance of y_i, and $b = y_1 - y_2$ estimates the bias. However, $E(b^2) = \mathbf{V}(y_1) + \mathbf{V}(y_2) + \mathbf{B}^2$. Thus another reasonable estimator is:

$$w_2 = v(y_2) \;/\; b^2. \tag{6}$$

Another possible estimator can be derived using the Taylor series expansion for $\mathbf{E}(1/x)$:

$$\mathbf{E}(1/x) \approx 1/\mathbf{E}(x) + \mathbf{V}(x)/\{(\mathbf{E}(x))^3\} \tag{7}$$

Let $x=b^2$. Then, $\mathbf{E}(b^2) = \mathbf{E}(y_1-y_2)^2 = \mathbf{V}(y_1) + \mathbf{V}(y_2) + \mathbf{B}^2$.

And, $\mathbf{V}(b^2) = \mathbf{V}((y_1-y_2)^2)$. Assume that y_1 and y_2 are normally distributed. Then $(y_1-y_2)/(\mathbf{V}(y_1)+\mathbf{V}(y_2))$ is distributed normally with mean $\mathbf{B}$ and variance 1. Thus the square of this quantity is distributed as a Chi-square with 1 d.f., and a Chi-square with 1 d.f. has variance 2. It follows that:

$$\mathbf{V}(b^2) = \mathbf{V}((y_1-y_2)^2) = 2(\mathbf{V}(y_1)+\mathbf{V}(y_2))^2 \tag{8}$$

Using [7] and [8], we find

$$\mathbf{E}\left[\frac{\mathbf{V}(y_2)}{b^2}\right] \approx \frac{\mathbf{V}(y_2)}{\mathbf{V}(y_1)+\mathbf{V}(y_2)+\mathbf{B}^2} + \frac{2\{\mathbf{V}(y_1)+\mathbf{V}(y_2)\}^2\mathbf{V}(y_2)}{\{\mathbf{V}(y_1)+\mathbf{V}(y_2)+\mathbf{B}^2\}^3} \tag{9}$$

As the first expression on the right-hand side of [9] is exactly the quantity we wish to estimate, another reasonable estimator is:

$$w_3 = \frac{v(y_2)}{b^2} - \frac{2\{v(y_1)+v(y_2)\}^2 v(y_2)}{\{v(y_1)+v(y_2)+b^2\}^3} \tag{10}$$

Examination of w_2 and w_3 reveals that it is possible for both of these quantities to exceed

$$w_u = v(y_2)/\{v(y_1)+v(y_2)\}. \tag{11}$$

This is undesirable because w_u is the weight attached to y_1 if y_1 is unbiased. As this is not the case here, the weight attached to y_1 should clearly be constrained to be less than or equal to that shown in [11]. This suggests two more estimators: $w_4 = \min(w_2, w_u)$ and $w_5 = \min(w_3, w_u)$.

Three additional estimators were developed using the following ad-hoc philosophy: After a sample is drawn, the "true value" of y_2 (the sample mean) is thought, with 95% confidence, to be within two standard errors of y_2. If y_1 is also within two standard errors of y_2, we cannot, on the basis of that sample, state that y_1 is biased because we cannot state that y_1 is significantly different than $\mathbf{Y}$. Thus we propose using w_u and acting as if y_1 is unbiased if it falls within 2 standard errors of y_2, and using either w_1, w_2, or w_3 if y_1 is not in an approximate 95% confidence interval for y_2. These estimators will be termed w_6, w_7, and w_8, respectively.

SIMULATION

In order to determine which estimator to recommend, we conducted a two-stage simulation experiment. At the first stage, 50 observations were drawn from a $\mathbf{N}(0,1)$ population, and 50 more observations were independently drawn from a $\mathbf{N}(\mathbf{B},\mathbf{V})$ population. These will be called the first stage samples. The estimates x_1 through x_8 (corresponding to weights w_1 through w_8) were computed for each first stage sample. Additionally, for each first stage sample we computed $x.$, the sample mean from the unbiased population, and x_u, the standard composite estimate. One thousand first stage samples were selected. At the second stage, independent bootstrap samples of size 50 were drawn with replacement from each of the two first stage samples. The estimates $z.$, z_u, and z_1 through z_8 were computed for each second stage sample. These correspond to $x.$, x_u and x_1 through x_8, except z denotes that the estimate is from the second stage sample. Squared errors were determined for each estimator from the second stage samples. Here, the deviations were taken about $x.$, the mean of the first stage sample. The bootstrapping procedure was carried out 50 times for each first stage sample. The squared errors for all 10 second stage estimators were summed (there were 50 deviations for each estimator, corresponding to the 50 pairs of bootstrap samples) and ranked. The estimator with the lowest sum of squared errors became x_9, the 11th first stage estimator (note that the form of x_9 varied between first stage samples, according to which estimator appeared superior in the second stage). Finally, the MSE's of $x.$, x_u, and x_1 through x_9 about the true mean, 0, were determined for the 1000 first stage samples.

Representative values of $\mathbf{V}$ were determined as follows: in Green and Strawderman (1986) an example is presented for a loblolly pine plantation for which a yield model gave a prediction of approximately 3700 ft^3/ac with a prediction variance of 176200. Suppose an inventory is taken and the coefficient of variation (CV) of the sample is 1.0 or 100%. Then if we let $x.=3700$, $s_x=3700$ and $s_x^2=13690000$. The ratio of the model prediction variance to the sample variance is then $176200/13690000 = 0.013$. For our simulation, the variance for the unbiased population is 1.0. To achieve the same ratio, we determined the variance of the biased population as $(\mathbf{V}/50)/1.0 = 0.013$, or $\mathbf{V} = 0.65$ (note 50 is the sample size and the model prediction is analogous to a sample mean). Similar calculations with CV=0.5 and 0.25 yielded $\mathbf{V} = 2.5$ and 10.0, respectively. Values for $\mathbf{B}$ were determined in a similar manner. For a CV = 1.0, we assume $s_x^2 =$

13690000. Suppose the bias of the model was 100 ft^3. Then the ratio of bias/variance is 100/13690000 = 0.000007. For the simulation, with a variance of 1 for the unbiased population, we must have **B** = 0.000007 to maintain the ratio. Simulation biases corresponding to biases of 500 and 1000 ft^3 were 0.00004 and 0.00007, respectively. For CV = 0.5, we found **B** = 0.00003, 0.00015 and 0.0003 to correspond to biases in the yield model of 100, 500 and 1000 ft^3, and for CV = 0.25, we found **B** = 0.0001, 0.0006 and 0.001 to correspond to the same respective yield model biases.

Given the above, we conducted the simulation with **B** = 0.00001, 0.0001, 0.001, 0.01, 0.1, 0.5, 1.0, and 10.0. The latter five values were chosen to investigate the behavior of the estimators when the model bias was larger than expected. For each value of **B** simulations were performed with **V** = 0.65, 2.5, and 10.

RESULTS

A summary of the results is presented in Table 1. The results for **B** = 0.00001 and 0.001 were virtually identical to those for **B** = 0.0001, so only latter are presented. Similarly, the results for **B** = 0.1 and 1.0 are not shown since they followed the trend already evident in the table. Each cell in the Table contains 4 values. The top value is the MSE of $x.$, the sample mean. The second value is the MSE of x_u, the usual composite estimator and the third value is the MSE of x_1. The bottom value is the MSE of x_9, the bootstrap estimator. MSE's are not shown for x_2 through x_8 because these estimators produced MSE's which were always very close to that of x_1.

TABLE 1. Mean square errors for four estimators given **B** and **V**. From top to bottom in each cell, the values correspond to $x.$, x_u, x_1, and x_9.

		B			
		0.0001	0.01	0.5	10.0
	0.65	0.021 0.008 0.014 0.019	0.019 0.008 0.012 0.016	0.021 0.099 0.024 0.022	0.019 36.827 0.019 0.019
V	2.5	0.020 0.015 0.017 0.019	0.020 0.014 0.017 0.019	0.021 0.035 0.022 0.022	0.019 8.978 0.019 0.019
	10.0	0.021 0.019 0.020 0.021	0.019 0.017 0.018 0.018	0.021 0.021 0.021 0.021	0.019 0.958 0.019 0.019

The values in Table 1 indicate x_1 performed as anticipated. When the bias was small, it yielded MSE's intermediate between $x.$ and x_u. When the bias was large and the MSE of x_u was large, x_1 was close to $x.$. The bootstrap estimator, x_9, tended to always be close to $x.$ in terms of MSE. In retrospect, we believe this to be true for the following reason: the MSE's of the second stage bootstrap samples were taken about $x.$. Thus we chose whichever estimator ($z.$, z_u, or z_1 through z_8) was closest to $x.$. Therefore the MSE of x_9 over the first stage sample should have been close to that of $x.$.

The values in the Table also indicate that the potential gain from using composite estimators decreases as the variance of the model estimate increases. This is to be expected. In addition, the effect of ignoring large biases decreases as the variance of the model estimate increases. This occurs because when the model estimate has a large variance, the weight attached to model estimate according to equation [11] is small and thus the effect of ignoring the bias is not as severe. When the model estimate has a small variance, equation [11] will result in a relatively large weight on the model prediction, and ignoring the bias in this case can produce very large errors.

CONCLUSIONS

For usual plantation yield prediction problems, the relevant portion of Table 1 is probably the first two columns (**B** = 0.0001, 0.01) and the first two rows (**V** = 0.65 and 2.5). Thus it is probably not necessary to account for the possible bias of the yield model. However, in situations where the relative bias is unknown, partially known, or thought to be moderately large, a composite estimator which accounts for the possible bias may be acceptable. Such an estimator yields an error which is lower than that of the sample mean when the bias is small, and about equal to that of the sample mean when the bias is large. If the bias is known to be relatively large, then although a composite estimator which accounts for bias might perform as well as the sample mean, there would be no justification for the use of a composite estimator so the sample mean should be used.

In this study we addressed the possibility of bias of the model estimate. As previously mentioned, another potential problem is correlation of the model estimate and the sample mean if the independent variables used in the model are derived from the sample. Preliminary results from testing with real data indicate that in the presence of correlation, accounting for model bias may be necessary in order for the composite estimator to yield a smaller error than the sample mean. We are currently studying this and plan to report on it at a future date.

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AN INTEGRO - DIFFERENTIAL EQUATION MODEL OF TREE HEIGHT GROWTH

David C. Hamlin[1] and Rolfe A. Leary[2]

ABSTRACT. The integro - differential equation

$$y' = -\,ay - b\int_{t_0}^{t} g(u)\,du + ct \tag{0}$$

is developed as a model of tree height growth. Equation (0) can be reduced to a second order linear differential equation with constraints $y_0 = y'_0 = 0$ on its initial conditions if $t_0 = 0$ and $g(u) = y$. The resulting differential equation can be calibrated directly from tree height - age data.

Replacing *a* with $(\alpha_1+\alpha_2*H_{50})$, *b* with $(\beta_1+\beta_2*H_{50})$, and *c* with $(\Gamma_1+\Gamma_2*H_{50})$ where H_{50} is height at age 50, results in a general equation for a family of site index curves. The coefficients α_1, α_2, β_1, β_2, Γ_1, Γ_2 were estimated from a set of proportional site index curves. The resulting model fits well, provides a representation of the pattern of height development, and offers good theorification potential.

INTRODUCTION

The work reported here focussed on constructing a model of tree height growth with properties reflecting the pattern of height development. Because the object to be modeled was change, differential equation models were appropriate.

Many successful forest growth models have been based on first - order differential equations (Richards 1959; Chapman 1961; Pienaar 1966; Pienaar and Turnbull 1973) and higher - order differential equations have been proposed (Hamlin and Leary 1987; Umemura 1984; Korf 1974; Nagumo and Sato 1965). In most cases however, the model has been expressed as a solution to the basic differential equation. Direct application of differential models of forest growth is still relatively new (Leary 1972; Moser 1973; Shifley *et al*. 1982; Garcia 1983; Lynch and Moser 1986; Hamlin and Leary 1987) although techniques for such application are readily available and are used routinely in other disciplines.

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THE MODEL

First - order differential equations have the general form:

$$y' = f(t,y) \tag{1}$$

where y is size and t is time, and thus represent change in terms of current size and time. In order to establish differences in growth among trees that are the same size at some time, but were not the same size at previous times, it is necessary to add a term to equation (1). Roston (1962) suggested an integro - differential equation model for populations which incorporates both current population size and a history of development:

$$y' = -ay - b\int_{t_0}^{t} g(u)\,du \tag{2}$$

in which $-ay$ represents inhibition of growth due to encroachment on space and the integral term provides a history of development. Interpreted in terms of individual tree height growth, equation (2) defines instantaneous change in height as a function of current size and an accumulation of past sizes.

Setting $g(u) = y$ and $t_0 = 0$ in equation (2) and differentiating results in a second - order, linear, homogeneous differential equation. The graphs of the solution to this differential equation show that equation (2) is not suitable for modelling the growth of healthy trees because the solutions are neither monotonic - increasing nor necessarily even positive for all times.

Adding a simple term (ct) to equation (2) gives:

$$y' = -ay - b\int_{t_0}^{t} g(u)\,du + ct \tag{3}$$

With $t_0 = 0$ and $g(u) = y$ equation (3) can be differentiated to give a non - homogeneous differential equation:

$$y'' + ay' + by = c \tag{4}$$

the solutions of which can have the desirable properties of an upper asymptote, monotonic increase, and sigmoid form.

Solutions to equation (4) are readily obtained:

$$y = y_p + A\exp(k_1 t) + B\exp(k_2 t) \tag{5a}$$

where y_p is a particular solution to equation (4) equal to c/b and is the asymptotic height , k_1 and k_2 are real eigenvalues of $m^2 + am + b = 0$, and A and B are constants. If $k_1 = k_2$ then:

$$y = y_p + A \exp(k_1 t) \tag{5b}$$

which, as Nagumo and Sato (1965) point out, is Mitscherlich's equation.

Inspection of equation (3) facilitates interpretation of the coefficients (a, b, c). Coefficient c can be viewed primarily as a genetically determined growth rate, with perhaps a small environmental component. Coefficient a can then be viewed as a damping of growth rate resulting from the greater energy requirements for moisture transport in taller trees. Coefficient b can be viewed as a damping due to accumulation of living biomass and the resulting increase in respiration, nutrients, or moisture required to maintain the tree.

Equation (4) was also proposed directly by Umemura (1984) who suggested that the acceleration of some standing crop (y'') is governed by a site productivity constant (c) which is reduced in proportion to the existing crop (y) and the current growth rate (y').

Equation (5a) or (5b) describes a family of curves; determination of a specific curve requires specification of the initial values of two of the three elements y_0, y'_0, and y''_0 after which A and B can be found to determine a specific member of the family. Umemura (1984) proposed the initial conditions $y_0 = y'_0 = 0$. We often require that $y_0 = 0$ in growth models. If $y_0 = 0$ then by equation (3) $y'_0 = 0$ must be true as well. The second requirement provides a stronger definition of time zero; a tree has neither height nor growth at time zero. Biologically, time zero is a seed just before germination.

The coefficients of equation (4), with the initial conditions above, can be estimated from stem analysis data using the multipoint boundary value approach (Leary 1972). Hamlin and Leary (1987) fit equation (4) to Douglas - fir (*Pseudotsuga menziesii*) height - age data with good results.

AN EXTENSION OF THE MODEL

It was hypothesized that if a, b, and c in equations (3) and (4) reflect the pattern of height development then a, b, and c would be related to some other property of the curve. As a test *a*, *b*, and *c* in equation (3) were made linear functions of height at age 50:

$$y' = -y(\alpha_1+\alpha_2*H_{50}) - (\beta_1+\beta_2*H_{50}) \int_{t_0}^{t} g(u)\, du + (\Gamma_1+\Gamma_2*H_{50})t \qquad (6)$$

where H_{50} is height at age 50. With $g(u) = y$ and $t_0 = 0$, the companion differential equation is:

$$y'' + (\alpha_1+\alpha_2*H_{50})y' + (\beta_1+\beta_2*H_{50})y = (\Gamma_1+\Gamma_2*H_{50}). \qquad (7)$$

Equation (7) was calibrated using data read from a set of proportional white pine (*Pinus strobus*) site index curves (Gevorkiantz 1957); coefficient estimates are given in table (1), and table (2) shows the resulting coefficients of equations (4) and (5).

Table 1. Estimates of the coefficients of equation (7) for white pine site index curves of Gevorkiantz (1957).

Coefficient	Estimate Value
α_1	7.1962E-2
α_2	9.1623E-5
β_1	1.2146E-3
β_2	1.2735E-6
Γ_1	-6.6711E-3
Γ_2	2.6384E-3

Table 2. Coefficients of equations (4) and (5) from values in table (1).

	Height at Age 50				
Coefficient	40	50	60	70	80
a	0.075626	0.076542	0.077459	0.078375	0.079291
b	0.001265	0.001278	0.001291	0.001303	0.001316
c	0.098864	0.125248	0.151632	0.178016	0.204400
Y_p	78.12	97.98	117.45	136.54	155.26
A	-154.29	-186.32	-216.07	-243.95	-270.26
B	76.18	88.34	98.62	107.41	115.00
k_1	-0.02499	-0.02461	-0.02427	-0.02395	-0.02366
k_2	-0.05063	-0.05192	-0.05318	-0.05441	-0.05562

The fit of equation (7) was good; the residual mean square was 0.36 from a total of 55 data points. Figure (1) shows both the observed and predicted curves. The relatively large deviations at age 20 result from our assumption that the curves pass through the origin. Apparently Gevorkiantz (1957) did not make that assumption in drawing the curves.

By way of comparison, the equation:

$$y = dH_{50}(1-\exp(ft))^{g} \qquad (8)$$

where d, f, and g are numerical constants, was calibrated using non-linear regression and the same data used for calibration of equation (7). The estimated values for d, f, and g were 1.946, -0.025, and 1.950 respectively. Equation (7) fit the data slightly better than equation (8), particularly in terms of residual sums of squares table (3). The maximum deviation occured at the same data point (SI = 80, age = 20) for both equations, which is probably an artifact of the data.

Fig. 1: Observed and Predicted Values From Equation (7)

Observed Values from Gevorkiantz (1957)

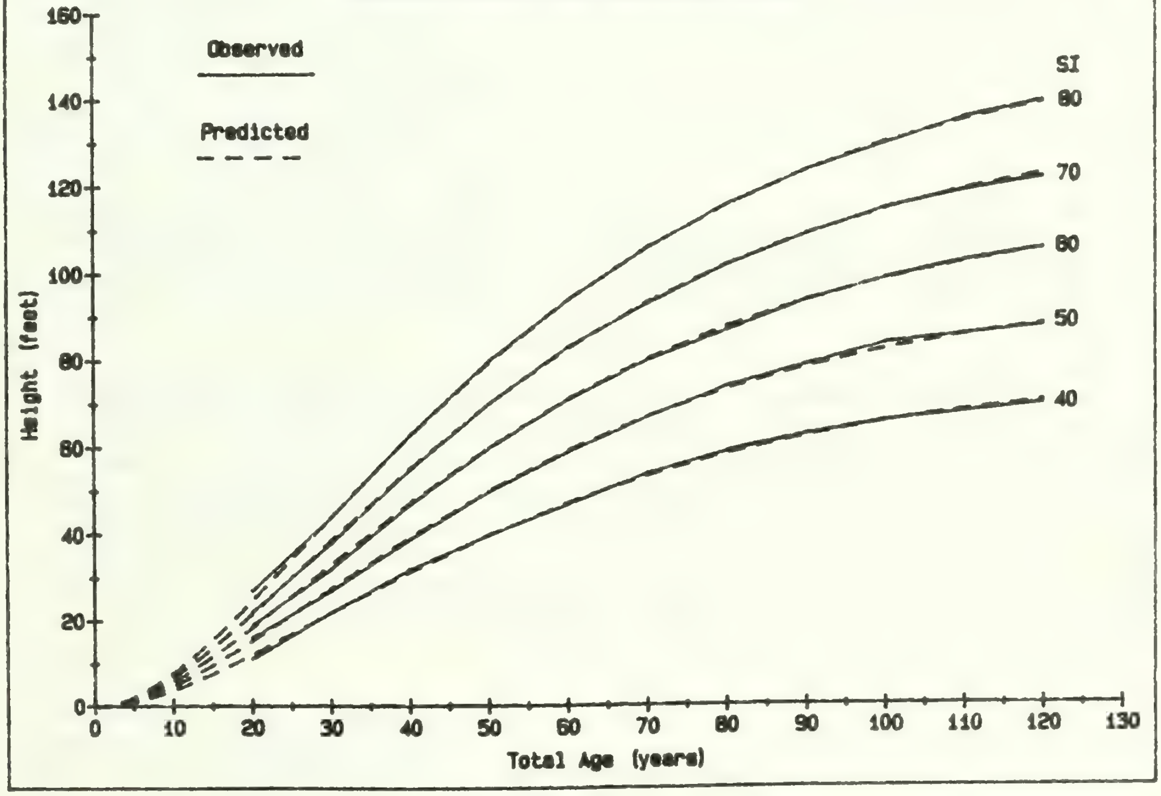

Table 3. Comparisons of fit of equations (7) and (8).
The same 55 data points were used for each.

Measure of Fit	Equation (7)	Equation (8)
$\Sigma(y_{obs}-y_{est})^2$	17.475	24.706
$\Sigma(y_{obs}-y_{est})$	0.407	3.152
$\Sigma\|(y_{obs}-y_{est})\|$	21.962	27.440
Residual mean square	0.357	0.475
Maximum Deviation	2.280	2.103

DISCUSSION

The fit of the differential equation model is slightly better than the fit of the more traditional -- equation (8) -- model. The differential model presents some other advantages over equation (8) as well, particularly in terms of interpretability of the coefficients.

Although it is easy to see that dH_{50} in equation (8) is the asymptotic height, interpretation of the other coefficients is less obvious. In contrast, the linearity of equations (6) and (7) makes the role of each coefficient clear and thus facilitates development of hypotheses about the biological meaning of the individual terms. For example if, as suggested above, coefficient c is a species growth constant, then one might expect the growth term $c = (\Gamma_1+\Gamma_2*H_{50})$ to be constant over a family of site index curves and damping terms -- $b = (\beta_1+\beta_2*H_{50})$ and $a = (\alpha_1+\alpha_2*H_{50})$ -- to decrease with increasing height at age 50. The coefficient estimates in table (1) do not bear this out however. Rather they show that the growth term increases with height at age 50 and that both damping terms increase, albeit very little, with height at age 50 as well.

It is important to remember that the data used here were not observations of tree height and age from sites of different quality. Rather, the data are expected heights from a set of proportional site index curves and as such reflect certain assumptions about the relationships between site quality and tree growth. Thus, the interpretation of the coefficients suggested above is not consistent with proportional site index curves. Whether the inconsistency can be attributed to misinterpretation of equation (6) or to an erroneous assumption of proportionality remains to be determined.

The integro - differential equation (3) also provides a basic framework for other models. This study used g(u) = y, but an allometric equation for annual litterfall could be substituted (Hamlin and Leary 1987). The extension of equation (3) to equation (6) is straightforward, and in addition to providing a model for a family of site index curves has been used to localize regional height growth models (Leary and Hamlin, 1987).

CONCLUSIONS

Based on the fitting of equation (7) to a set of site index curves, it is apparent that the coefficients of equation (3) reflect the pattern of height development.

The integro - differential equation model of tree height growth is seen to have two desirable properties: high theorification potential and good fits to existing height - age curves. That a model should fit observed phenomena is axiomatic. The major advantages of the integro - differential model over more traditional models are its adaptability within the basic model, and the ease of interpretation of numerical constants and terms.

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OPTIMAL PREDICTION OF DOMINANT HEIGHT CURVES BASED ON AN ANALYSIS OF VARIANCE COMPONENTS AND SERIAL AUTOCORRELATION

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ABSTRACT. We discuss how the height development of dominant trees can be predicted using site information and available height measurements. The suggested prediction procedure is based on statistical models which explicitly describe the major fixed and random components in the variation of height curves. The average height at a given age is a function of site variables. Deviations from the average height curve have a special variance-covariance structure. First, the deviations of different trees within a given stand are correlated. This correlation can be described by decomposing the random error at a given age into random stand and tree effects. Furthermore, the random stand and tree effects are correlated over time. The autocorrelation over time can be described, for instance, using multivariate methods to estimate a general covariance matrix, or using random parameters in the height curve. After the model parameters have been estimated, the height development of a given stand can be predicted using standard statistical prediction methods which optimally combine observations of site variables and any available height measurements. Also the variances of the prediction errors will be obtained.

INTRODUCTION

Accurate prediction of height growth of dominant trees is important when we try to describe the productivity of a tree species in a given stand. Traditionally dominant height has been predicted using site index as a fixed (i.e. non-random) auxiliary variable (parameter). From a statistical point of view, the main problem in traditional site index methods is that a deterministic relationship is assumed and distributional relationships which exist in reality are not recognized. A proper statistical analysis of the random variation in height growth is very difficult using such site index methods.

In this paper we describe height growth using a single statistical model which explicitly includes all major components in height variation. The model is based on the same ideas used by Lappi (1986) to analyze and predict stem form variation of Scots pine. The fixed part of the model describes the mean height at a given age as a function of site variables. Random deviations from the average height curve have a special covariance structure. First, the deviations of different trees

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within a given stand are correlated. This correlation can be described by decomposing the random error at a given age into random stand and tree effects. Furthermore, the random stand and tree effects are correlated over time.

We thus have three different height curve types: population height curve, stand height curve and tree height curve. The population height curve is the deterministic (fixed) average height curve as a function of site variables. Stand and tree curves are assumed to be random variations about the population curve with a covariance structure that can be utilized in predicting stand or tree heights.

When the mean function and covariance structure have been estimated, the complete stand and tree height curves can be predicted from available height measurements using linear prediction theory (see, e.g., Rao 1973). More specifically: If $\mathbf{y}_1$ is an observed random vector with mean μ_1 and variance matrix $\mathbf{\Sigma}_1$ and y_2 is an unobserved random variable with mean μ_2 and variance σ_2^2, and $\mathrm{cov}(y_2,\mathbf{y}_1') = \sigma_{21}$, then the best linear unbiased predictor of y_2 is:

$$\hat{y}_2 = \mu_2 + \sigma_{21}\mathbf{\Sigma}_1^{-1}(\mathbf{y}_1-\mu_1), \tag{1}$$

and the variance of the prediction error is:

$$\mathrm{var}(y_2-\hat{y}_2) = \sigma_2^2 - \sigma_{21}\mathbf{\Sigma}_1^{-1}\sigma_{21}'. \tag{2}$$

If $\mathbf{y}_1$ and y_2 have a joint multivariate normal distribution, then the predictor is the conditional expectation and, hence, the best possible predictor.

The basic prediction formula (1) can be used to predict average dominant height at a specified age (e.g., at the index age) in a given stand using available height measurements at any age. Other site variables are assumed to be fixed; their influence can be taken into account by assuming that means μ_1 and μ_2 can depend on them.

In the following we will discuss different ways that the means and covariance structure can be specified. See Ware (1985) for a discussion of different model specifications for growth curves and Goldstein (1986) for information on general hierarchical models. Some example computations are made using the loblolly pine (*Pinus taeda* L.) dominant height data described in Bailey et al. (1985). We only used data from trees which were at least 16 years old (122 trees from 64 stands, one or two trees in each stand). The method of Carmean (1972) was used to estimate true height curves from the stem analysis data. Dyer and Bailey (1987) found that this method was best among six methods compared. Errors in these estimated heights were not taken into account in our analysis.

MULTIVARIATE MODEL

In order to predict with equation (1) we must specify the model in such a way that we can estimate the mean height curve and variances and covariances of the stand and tree effects. The simplest way to do this is to use a multivariate formulation where height at each age is treated as a separate variable. If we do not take site variables into account we get the following model for the height (h_{kit}) of tree i in stand k at age t:

$$h_{kit} = \mu_t + b_{kt} + e_{kit}, \tag{3}$$

where μ_t is the population mean height at age t over all stands, b_{kt} is the random stand effect ($\mu_t + b_{kt}$ being the dominant height of stand k at age t), and e_{kit} is the random tree effect and is uncorrelated with b_{kt}.

For this model we must estimate the variances of b- and e- effects for each age, and covariances between different time points. This can be done, for instance, by estimating the variance components of h_t and h_t+h_s for each t and for each combination t and s with the analysis of variance method (Searle 1971). The between-stand and within-stand covariances can then be estimated using the equation (Searle and Rounsaville 1974):

$$\mathrm{cov}(h_t, h_s) = [\mathrm{var}(h_t+h_s) - \mathrm{var}(h_t) - \mathrm{var}(h_s)]/2. \tag{4}$$

Both autocorrelation (for equal time difference) and variance increase as stands get older (Table 1). For young trees the between-stand variance is about the same as the within-stand variance, but it increases much faster with age than does the within-stand variance. Stand effects are more correlated than tree effects.

TABLE 1. Between-stand and within-stand standard deviations (on the diagonal) and correlations estimated using observations where heights were available up to the age of 16 years.

	between-stand (b-effects)								within-stand (e-effects)							
age																
2	**1.3**								**1.8**							
4	.89	**2.5**							.71	**2.4**						
6	.81	.98	**3.2**						.60	.85	**3.1**					
8	.78	.90	.96	**3.8**					.50	.78	.87	**3.1**				
10	.71	.86	.94	.99	**4.3**				.48	.74	.77	.88	**3.0**			
12	.66	.82	.89	.94	.97	**4.7**			.41	.69	.73	.82	.94	**2.9**		
14	.66	.81	.88	.92	.96	.99	**5.3**		.36	.62	.68	.77	.85	.94	**2.8**	
16	.65	.76	.85	.88	.93	.97	.99	**5.5**	.31	.57	.64	.74	.80	.87	.93	**2.9**
age	2	4	6	8	10	12	14	16	2	4	6	8	10	12	14	16

Between-stand and within-stand covariance matrices can be analyzed further in terms of principal components (see, e.g., Morrison 1976). The most important component of variation is not the variation associated with a multiplicative constant as assumed in anamorphic height/site index models. The relative differences between stand heights generally decrease over time (Figure 1a).

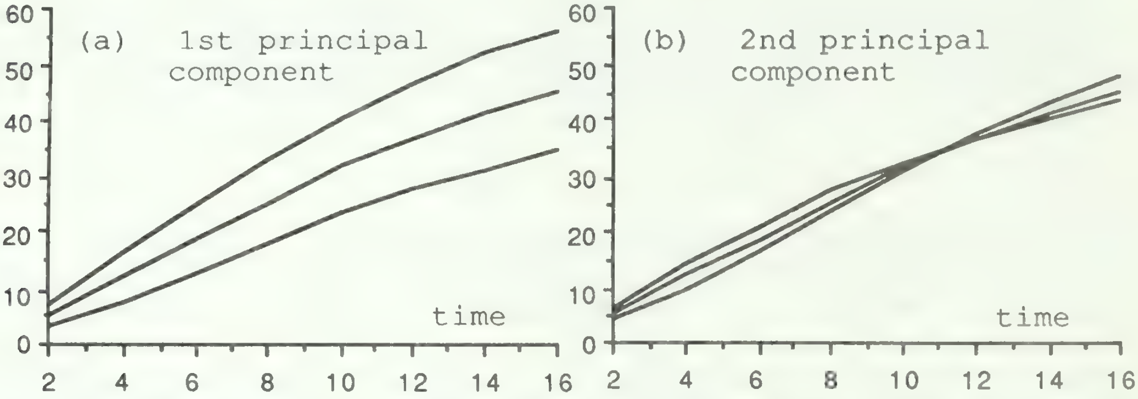

Figure 1. Variation in loblolly pine stand height around the mean in the directions of the first two characteristic vectors. The principal components are given values ± two times their standard deviations. The first two components account for 94.4 % and 4.2 % of the total variance, respectively.

When the random effects model (3) is used to predict dominant stand height from sample tree measurements, we need to evaluate the variance-covariance matrix of sample tree heights ($\mathbf{\Sigma}_1$ in Eq. 1) and the covariance vector between sample tree heights and stand height at the time point of interest (σ_{21} in Eq. 1). The variances and covariances of sample tree heights can be calculated as:

$$\text{var}(h_{kit}) = \text{var}(b_{kt}) + \text{var}(e_{kit}), \text{ and} \qquad (5)$$

$$\text{cov}(h_{kit}, h_{kjs}) = \text{cov}(b_{kt}, b_{ks}) + \text{cov}(e_{kit}, e_{kjs}). \qquad (6)$$

If sample tree measurements are for different trees ($i \neq j$), the covariance between e-effects, the last term in (6), is zero. The covariance between a sample tree height at age t and stand height at age s (a general element of σ_{21}) is:

$$\text{cov}(h_{kit}, b_{ks}) = \text{cov}(b_{kt}, b_{ks}). \qquad (7)$$

Utilization of site information is very easy in the multivariate set-up. The height at each age can be regressed on site variables, then this regression equation gives the mean μ as a function of site variables.If μ is a linear function of the parameters, standard methods of mixed linear models can be used to estimate both the fixed parameters and variance components.

In the multivariate set-up estimation of the means μ_t and the covariance structure is simple if we have enough complete records for the whole time range of interest. The model parameters can be estimated by the maximum likelihood method also in cases when the records are not complete (e.g., using the EM algorithm implemented for repeated measurement models by Jennrich and Schluchter 1986). But using a full multivariate model, we cannot extrapolate above the data. Also a more parsimonious model with fewer and more easily interpretable parameters is theoretically more appealing. The transformation from the multivariate model to a univariate model can be achieved if both the mean μ_t and covariances between different time points can be explicitly presented as a function of age instead of separate parameters.

MEAN HEIGHT CURVE AS A FUNCTION OF TIME

When specifying models for the mean function $\mu(t)$, all accumulated knowledge from previous height curves can be utilized. The two main decisions determining the available estimation methods are: i) should we use logarithmic or arithmetic measurement scale, ii) is the model linear in parameters. These decisions are interrelated, because a logarithmic scale is often adopted in order to linearize the model.

If the model is estimated in the logarithmic scale, we need a special correction in order to get unbiased predictions in the arithmetic scale. With a structured random part in the model, the bias correction is not similar to the standard regression case (Lappi 1986). The main difficulty with nonlinear models would be that the available algorithms for simultaneous estimation of parameters in mean and covariance functions are developed for the linear case. A practical and also theoretically justifiable (i.e. consistent) method would be to first estimate the mean function using nonlinear least squares, and then use observed residuals as if they were the true residuals in the estimation of parameters of the covariance structure.

The mean function can also be a function of site variables. For instance, we can first specify a reasonable growth curve without site variables, and then express the parameters as a function of site variables (see Ware 1985). Or, if the site variables just classify sites into soil types, then we can have different parameters for each group.

With our sample data we used Richards' (1959) equation to describe the mean height:

$$\mu(t) = A[1-\exp(-kt)]^d \ . \tag{8}$$

Least squares estimates of A, k and d computed by Gauss-Newton method (Kennedy and Gentle 1980) were 70.8, 0.0826 and 1.40 (only trees at least 16 years old were used; heights measured in feet).

SPECIFICATION OF THE COVARIANCE STRUCTURE

In order to have a more parsimonious presentation for the covariances of the stand and tree effects we must specify how they are generated. The two main alternatives to describe the autocorrelation over time seem to be either to assume a simple time series model or to assume a model having random parameters.

The difference between the actual dominant height and the mean function has two special features when considered as a time series. First, the data consists of several realizations of the process. Second, the growth has a natural starting point and life span. Thus, the random part of the growth process cannot be adequately described as a stationary process. An adequate model would, in principle, be similar to the repeated measurement model of Mansour et. al. (1985), with variance component structure for each time point and nonstationary autoregressive structure over time. Their model did not, however, adequately describe our covariance structure. Thus we proceeded using a random parameters model.

If the variances and covariances of the random parameters are to be estimated by standard methods, the random part of the model should be linear in random parameters. On the other hand, the random stand and tree height curves might be reasonably obtained by using the same function as for the mean curve but with different parameters. A possible way to combine these two requirements is to linearize the model with respect to the parameters by a first order Taylor series around the population parameters. Thus we get the model:

$$h_{ki}(t) - \mu(t) = \mathbf{g}(t)'\mathbf{b}_k + \mathbf{g}(t)'\mathbf{c}_{ki} + e_{ki}(t), \qquad (9)$$

where $\mu(t)$ is the mean function (8) whose parameters are assumed to be known at this point, $\mathbf{g}(t)$ is the gradient vector of $\mu(t)$ with respect to the parameters (A, k, d) evaluated at the population parameters, $\mathbf{b}_k$ is the random parameter vector for stand k (approximately the difference between the stand parameters and population parameters), $\mathbf{c}_{ki}$ is the random parameter vector for tree i in stand k, and $e_{ki}(t)$ is the random error which does not correlate with $\mathbf{b}_k$ or $\mathbf{c}_{ki}$, or over time.

Prior to the general availability of such maximum likelihood estimation programs as those of Jennrich and Schluchter (1986, the program will be distributed by BMDP) and Goldstein (1986), the variance-covariance matrix of parameters in models like (9) can be estimated by adjusting the method of Rao (1975) if there are 'enough' measurements for each individual (tree). Rao estimates a simple (not hierarchical like ours) covariance matrix of parameters by first computing (generalized) least squares estimates for each individual. Then the covariance matrix is estimated by subtracting the covariance matrix of estimation errors from the sample covariance matrix of parameters.

Similarly, the covariance components of parameters can be estimated by first estimating the covariance components of the parameter estimates and then by subtracting the covariance matrix of estimation errors from the first stage within-stand covariance matrix. Trees in our sample data were so young that if three parameters were estimated for each tree then parameter estimates would have such large variances that the variance components of parameters could not be reliably estimated. Hence, we used only trees with age 16 years or more; with maximum likelihood all the data could be utilized. The resulting estimates for the covariance matrices (Table 2) of the random parameters will produce quite well the multivariate covariance matrices (Table 1), and the covariances (as well as the mean function) can be extrapolated above the data available.

TABLE 2. Estimated standard deviations (on the diagonal) and correlations of the stand parameters ($\mathbf{b}_k$) and tree parameters ($\mathbf{c}_{ki}$) for model (9). The parameters are indicated by the corresponding parameters in the mean function (8), e.g., the coefficient of $\partial\mu/\partial A$ is indicated by A. Standard deviation of $e_{ki}(t)$ was estimated to be 1.0 feet.

stand parameters

A	**13.6**		
k	-.79	**.0263**	
d	-.63	.827	**.235**
	A	k	d

tree parameters

A	**8.74**		
k	-.85	**.0203**	
d	-.42	.69	**.228**
	A	k	d

The estimated mean function (8) and the covariance function implied by (9) were used to predict the stand height at age 16 using the height of one sample tree at age 8. As a comparison, the stand height was also predicted by an polymorphic-disjoint site-index equation which Bailey et al. (1985) found to be best for the same data. Prediction errors were evaluated using the other tree in the same stand. The error variance of the stand height was estimated for both methods by subtracting the within-stand variance (var[e(16)]) from the sample error variance of the test trees.

Mean square error for the our method was 81% of the mean square error for the site-index method (root mean square errors were 3.5 and 3.9 feet, respectively). The theoretical standard deviation of the prediction error calculated using (2) was 3.5 feet, thus agreeing with the observed root mean square error. Note that if the same trees were used to predict stand height and evaluate the prediction errors, then the errors in stand height and tree height prediction cannot be properly separated because the tree effects of sample and test trees would be correlated. With our model the predictor is also different if the heights of the sample trees are to be predicted.

CONCLUDING REMARKS

The proposed approach for predicting stand height curves has several theoretical advantages over traditional site index methods. First the major features in height curves (the effect of site variables, distribution of tree heights around stand mean, distribution of stand means in different stands, the autocorrelation over time) can be taken into account. The predicted height at a specific index age can still be used as a descriptive indicator of site quality, but it does not have any role in the prediction method. In spite of the detailed structure of the model, height curves can be predicted with very few measurements in a given stand (e.g. one), and the predictor optimally combines the site information and tree measurements. The utilization of any time invariant stand information (e.g, genotype of the planting stock) is also theoretically straightforward. Utilization of varying stand information requires more complicated analysis. Preliminary empirical results indicate that the proposed method will work well in practice.

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METHODS FOR LOCALIZING REGIONAL GROWTH MODELS FORMED AS SECOND ORDER DIFFERENTIAL EQUATIONS

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Abstract. When regional forest growth models are formed as second order differential equations, they can be adjusted to local conditions by making the numerical constants functions of site properties and by making the initial conditions governing the solution reflect current growth. A general height growth model is calibrated using a multi-point boundary value problem approach in such a way that the numerical constants are functions of depth of silt over a layer of chert. Predictions of height growth based on local soil conditions can be further improved by taking periodic measurements of height and height growth to restart the differential equation solution. The methodology is briefly demonstrated using black walnut height growth information from southern Illinois.

INTRODUCTION

Growth models calibrated from a number of data sources spread across an entire region, e.g., PROGNOSIS (Stage 1973) and STEMS (Belcher et al. 1982), have been developed in the last decade. These regional, or generalized, models facilitate regionwide analyses of timber resources for national forest plan preparation, Resources Planning Act timber inventory assessments, and other purposes. Regional models require large quantities of data for calibration, more than is typically available from a single source. Because calibration data come from an entire region, the models often have regionally unbiased but locally inaccurate (possibly both biased and imprecise) predictive power. The lack of local accuracy led Stage (1981), Gertner (1982, 1984), Smith (1983), and Holdaway (1985) to suggest ways to adjust regional models to local conditions. Local accuracy deficiencies have also been used to suggest the need for two classes of growth models: generalized models for regional analyses, and species and site-specific models to guide silvicultural decisionmaking. In this paper we present a method for localizing a model expressed as a second order differential equation so that it can be used both on a regional and local basis.

BACKGROUND

Most forest growth models calibrated from permanent growth plots are predicated on the assumption that site productivity is constant. Kimmins (1985) borrows the notion of "future shock" from Tofler to warn that

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foresters should proceed with caution when doing long range planning under that assumption.

In such a situation, it is important to carefully examine how growth models incorporate so-called "localizing" information. We contend one should select models that: a) are capable of incorporating properties of the environment that are expected to change both from place to place and time to time, and b) also easily accommodate short-term information feedback for continuous fine-tuning of the model.

Second order, linear, ordinary differential equations are a source of such models. Second order differential equation models can be localized in either or both of two ways: a) by adjusting differential equation numerical constants to reflect local site and environmental conditions ("here"), and b) by using local information about the current state of the tree or stand being modelled, the current rate of change of the tree or stand state, and tree or stand age ("here and now"). The latter information is used to modify the initial conditions governing equation solution. We demonstrate with a brief example how local information about soil properties can be used to modify the numerical constants in a height growth model, and how periodic observations of height and height growth can be used to form new initial conditions governing the projected height of black walnut (Juglans nigra) trees growing in southern Illinois[2]

THE GROWTH MODEL

The proposed growth model has the following form (Hamlin and Leary 1987):

$$d^2h/dt^2 = - a\, dh/dt - b\, h + c \qquad (1)$$

where d^2h/dt^2 designates rate of change of height growth,
dh/dt designates rate of change of height (height growth),
h designates total tree height, and
a, b, c denote numerical constants that characterize general environmental conditions.

If $a = .90$, $b = .0053$, and $c = 5.0$ in equation (1), an entire family of height-age relations is represented. A specific height-age relation is only fixed after initial conditions, typically on dh/dt and h, are specified. If the values of the numerical constants and initial conditions can be adjusted to reflect local conditions, equation (1) will provide a means to predict local height-age relations. We discuss first how to make the numerical constants reflect local, site-specific conditions. We then discuss how the initial conditions can be used to further refine the predictions on the basis of recent growth information.

LOCALIZING NUMERICAL CONSTANTS ("HERE')

If we wish to modify the numerical constants in equation (1) to make it reflect local conditions, what characteristics of a locality should be used? Historically, scientists have used a number of different approaches to categorize the spatial variation of forest growth patterns. One general approach categorizes growth patterns based on discrete geographical or ecological relations. An example is height growth patterns based on habitat types in northern Idaho (Monserud 1984). The other general approach expresses growth patterns as continuous functions of biogeophysical, synecological, or, more commonly, edaphic properties of the site (e.g., Carmean 1975, Hagglund 1981, and others). In the "here-now" sense of localizing a growth model, making the growth model numerical constants represent local conditions amounts to focusing on the "here" dimension.

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[2] We thank Willard Carmean for alerting us to the existence of this information and Robert Cecich for permission to use the archived data.

Our startegy for making a "here" adjustment is to use the normal kind of information collected in soil/site-growth studies: stem analysis, or height to whorl, information on a number of trees on each plot, and height-age coordinate pairs for each tree. For initial screening we fit equation (1) to the mean height-age data sets for each plot. The result is an estimate of a, b, and c for each plot that reflects the pattern of height growth that summarizes the local site and environmental conditions. In conjunction with the stem analysis, an analysis of factors of the soil (physical and chemical properties), the site (physiographic class, spatial orientation), and properties of the location must be undertaken to identify and measure those factors thought to account for variation in a, b, and c.

As a test case, we use data from a study of black walnut initated by W. H. Carmean (Carmean 1966), and reported on by Losche (1973), Losche and Schlesinger (1975), and included in Schlesinger and Funk (1977). The study examined soil and site factors affecting the height growth of 25-30-year-old plantation black walnut at 60 different planting sites in southern Illinois. All told 255 trees, typically 4 or 5 per plot, were felled and detailed stem analysis measurements taken. On each plot three pits at least 40 inches deep were dug to measure physical soil properties. Sites were grouped into two classes: 1) floodplains with more than 40 inches to gravel and upland sites, and 2) floodplains with less than 40 inches to an impervious layer (typically a mottled zone). For this paper, we use information from three floodplain plots having different thickness of silt over a layer of chert.

Our objective is to develop equations to predict numerical constants a, b, and c in equation (1) using thickness of silt over a layer of chert as the predictor variable. We fit equation (1) to the 26 mean height-age observations for each of three plots. The estimated thicknesses of silt over chert were 12, 18 and 24 inches. We used a multipoint boundary value approach (Hamlin and Leary 1987, Leary 1970, Leary 1972, Leary and Skog 1972). The results were as follows:

silt	numerical constant estimates			goodness of fit measures		
thickness	a	b	c	RMS	SUM(dev)	SUM|dev|
12	.5635	.0519	.9537	.016	-.46	2.58
18	.5329	.0702	1.837	.19	-1.93	7.92
24	.360	.0342	1.361	.18	-.8	7.84

We plotted the estimates for each constant over silt thickness and, for preliminary analysis, hypothesized a linear relation between silt thickness and each numerical constant. Some of the graphical analyses did not appear linear. However, from experience, we know that estimates of a, b and c can be correlated and compensatory. For example, a large value for c can be compensated for by larger values for the damping coefficients a and b.

To construct the general equation to predict black walnut height using age and silt thickness we used the following system of equations:

$$d^2h_1/dt^2 = -(a_1+a_2*12)dh_1/dt - (a_3+a_4*12)h_1 + (a_5+a_6*12)$$

$$d^2h_2/dt^2 = -(a_1+a_2*18)dh_2/dt - (a_3+a_4*18)h_2 + (a_5+a_6*18) \quad (2)$$

$$d^2h_3/dt^2 = -(a_1+a_2*24)dh_3/dt - (a_3+a_4*24)h_3 + (a_5+a_6*24)$$

$$da_i/dt = 0 \text{ for } i = 1,6.$$

The original 72 height-age observations formed the boundary conditions governing the estimates of initial conditions for the trivial differential equations, e.g., $da_1/dt = 0.$, etc., above. Heights for trees on plot 1, h_1, (12 inches to chert) formed the boundary conditions for the first equation in system of equations (2), heights for trees on plot 2, h_2, (18 inches to chert) formed the boundary conditions for the second equation, and heights for trees on plot 3, h_3, (24 inches to chert) formed the boundary conditions for the third equation. Fitting was based on the following minimization:

$$\min(\Sigma(h_1(\text{pred})-h_1(\text{obs}))^2 + \Sigma(h_2(\text{pred})-h_2(\text{obs}))^2 + \Sigma(h_3(\text{pred})-h_3(\text{obs}))^2)$$

Results of the fitting process are as follows:

$a_1 = 0.256$ $a_2 = .00954$

$a_3 = 0.056$ $a_4 = -0.000525$

$a_5 = -0.205$ $a_6 = 0.0829$

Other fit statistics are: residual mean square = 0.85, sum of deviations = -3.6, sum of absolute deviations = 55.5, maximum deviation = 2.6, average absolute deviation = 0.77.

Convergence to a 0.0001 absolute change in a numerical constant occurred in 13 iterations. As expected, the lack of fit as measured by residual mean square increased when the three data sets were combined. Much of the increase can be attributed to ages 5 to 15 in the plot with 18 inches of silt over chert (Figure 1). Thickness of a silt layer over chert has such a significant effect on black walnut height growth that the numerical constants in a height-growth equation can be made simple linear functions of it. Of course, the relation is probably not just a function of thickness; no doubt other factors also influence walnut height growth. But it is doubtful that any have as much effect as thickness of silt over chert. Coefficients of the damping (dh/dt and h) terms should decrease as silt thickness increases. Thus, both a_2 and a_4 should be negative. Unexpected is the positive value for a_2. However, we used only three of 60 available plots. The observed and predicted heights for the tree data sets are compared in Figure 1. On the basis of this limited trial, we offer the following equation as a conjectured relation between black walnut height, thickness of silt over chert, and time:

$$d^2h/dt^2 = (-.205+.0829*s) - (.256+.00954*s)dh/dt - (.056-.000525*s)h \quad (3)$$

where d^2h/dt^2 designates rate of change of height growth,
dh/dt designates the rate of change of height (height growth),
h designates total tree height, and
s designates inches of silt over chert.

We conclude that it is possible to model height growth using a second order differential equation having numerical constants that are functions of the soil conditions specific to a particular place ("here").

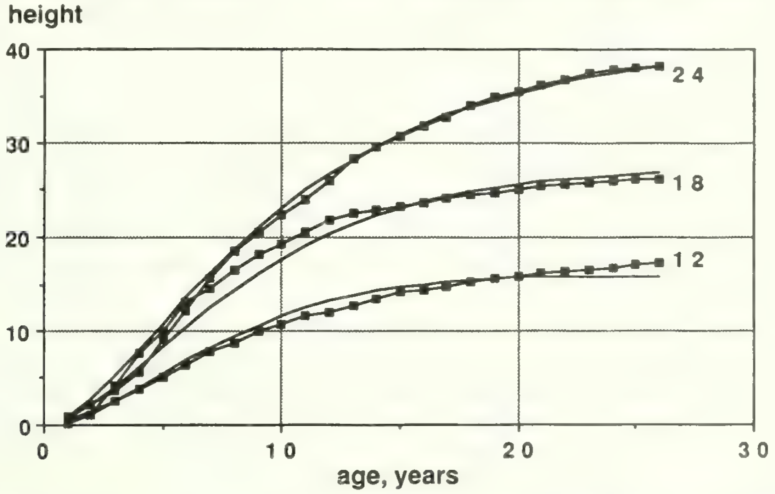

Figure 1. Predicted and observed heights of black walnut trees growing on bottomland soils in southern Illinois having different thicknesses of silt over a layer of chert.

LOCALIZING INITIAL CONDITIONS ("HERE-NOW')

We consider now the the second manner by which growth models formed as second order differential equations can be made to reflect local conditions. In the sense of "here-now" adjustments to growth models, we focus on both the "here and now" dimensions.

While the development of relations between site factors and numerical constants in growth models is typically based on research, is expensive, and long term, the adjustment of initial conditions governing the solution of growth models can become a regular part of forest operations. It may require little more than an increment borer and height measuring device to collect the basic data.

Second order differential equations require two initial conditions to specify a solution: typically a value of h (height) and a value of dh/dt (height growth) at the current time. These values are easy to estimate at stand establishment (say, height = 0.5 feet and dh/dt = 0). But, where does one get the most recent information about h and dh/dt at later ages? It can be collected using a calibrated pole, or, if the trees are too tall for a pole, a few trees can be felled for accurate measurement of h, and twigs from the tops of trees can be taken back to the lab for sectioning and analysis to get an accurate estimate of the current dh/dt. Current information on tree height can then be used to correct the latest height estimate (given by solving equation (3) using numerical constants that reflect the peculiar soil conditions of a location). The corrected height and the latest information on height growth can then be used to make a new projection of height growth from the current time forward.

One should check tree and stand development as a standard part of management. This is especially true if plans have been made using values projected by mathematical models. One can correct model projections as often as one wishes. However, it seems especially advisable to check estimates and make corrections after unusual events such as a prolonged period of low rainfall, an outbreak of a defoliating insect, or, for drainage sensitive soils, a period of excessive rainfall.

Consider the following example. Soil analysis showed another area with about 24 inches of silt over a zone of chert. We tested three strategies for collecting initial condition information to predict height at age 26 using equation (3): 1) seedling height and seedling growth rate (dh/dt) (columns 3 and 4 below), 2) height and height growth rate measured at age 6 (columns 5 and 6), 3) height and height growth rate measured at age 12 (columns 7 and 8), and height and height growth rate measured at age 18 (columns 9 and 10).

observed		***predicted heights using starting conditions***							
age	height	h	dh/dt	h	dh/dt	h	dh/dt	h	dh/dt
1	2	3	4	5	6	7	8	9	10
1	.2	.96	0.						
2	2.0	2.8							
6	9.3	13.5		9.3	1.83				
8	13.0	18.7		13.5					
12	20.3	26.7		22.5		20.3	1.75		
14	23.8	29.6		26.2		23.8			
18	27.9	33.9		31.6		29.8		27.9	0.95
26	35.5	38.2		37.4		36.6		35.2	
30	---	39.4		38.8		38.3		37.4	
40	---	40.6		40.4		40.2		40.0	
50	---	41.0		40.9		40.9		40.8	

Height growth rate was estimated by the average growth over the last two years, as might be done in the field. Using strategy 1), with s = 24 inches, and seedling height information, we can estimate height at age 26 within 2.7 feet (38.2-35.5). If we take a temporary plot and measure the height at age 6 and the average growth rate over the previous two years, we can estimate height at age 26 within 1.9 feet. A measurement of height and height growth at age 12 allows an estimate at age 26 to within 1.1 feet. The estimated heights at age 50 are within 0.2 feet. However, the maximum height predicted by the equation is given by c/b in equation (2), and is not influenced by the initial conditions. In sum, one may wish to make several corrections to the estimate of height, and/or height growth during the life of a stand.

DISCUSSION

Several points are relevant to the above method for localizing regional growth models in the form of equation (2):

1) Those interested in having regional growth models reflect local conditions should understand that "localizing" doesn't just happen. It takes additional research, and it takes local information--the responsibility of the user. Acquiring both kinds of information can be time consuming and expensive.

2) We suggest that equation numerical constants be made functions of site properties that may be different from place to place, but not very different over short time periods (human time, not geologic). Further, initial conditions monitoring should be based on site properties that can change greatly in both time and space, and are difficult to predict (e.g., annual rainfall, defoliating insect outbreaks, etc.).

3) Equation (3) is still linear in the dependent variable (h), and can be solved in closed form for easier evaluation.

4) Our approach to using information on height and height growth to restart the equation solution appears to generalize Alban's (1979) method of predicting height at age 50 from height growth above 8 feet.

5) Equation (3) is a hypothesis of the relation among walnut tree height, tree age, and soil conditions. Testing the hypothesis should involve making deductions from what equation (3) asserts, and checking those deductions against nature. For example, if we have 40 inches of silt over a layer of chert, we predict a height of about 70 feet at age 26. This is well within the range of observations for walnut in southern Illinois.

6) Our method of calibrating second order ordinary differential equations with numerical constants that are functions of site properties requires a large amount of computation. It requires that each observation be expressed as a separate differential equation. In order to apply the multi-point boundary value problem method of solution, each equation must be replicated as many times as there are unknown numerical constants (6 in this case) plus 2. Thus, in solving the above problem we had to repeat the integration of 96 first order differential equations from time 0 to 26, a total of 13 times. If we used all 60 of the black walnut plots with the same equation we fit above, we would have to integrate 1008 first order differential equations. Such large numbers of differential equations can be solved efficiently using new vectorized supercomputers. The examples in this paper were done on an IBM-AT microcomputer running TURBO-Pascal. Some of the differential equations are trivial (48 out of 1008). However, as the number of observations increases trivial equations comprise a small percentage of the total number.

7) We could also have made numerical constants functions of tree height at age 25 years. However, by making them functions of soil characteristics we are able to predict the capacity of bare land to grow walnut.

8) The second order differential equation we developed was for height growth; however, it can probably also be used for other tree and stand properties such as diameter or basal-area growth.

CONCLUSIONS

Second order differential equations are well-suited to serve both as regional models of tree growth and as local models of growth. The equations are localized in the "here" sense by making the numerical constants functions of factors that may change a great deal as one moves from one place to another, but in any one place they change slowly over time. A new approach to calibrating ordinary differential equations with site-dependent numerical constants shows promise in helping localize the equations. The initial conditions, on h and dh/dt, should be used to periodically reproject growth in light of the effects that recent, unpredictable events have had on past growth, thus localizing in the "here-now" sense.

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MODELING GROWTH AND MORTALITY PROBABILISTICALLY USING LOGISTIC REGRESSION

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ABSTRACT. Logistic regression analysis can be used in forestry to model growth and mortality simultaneously using a single probabilistic function. To fit such an equation, growth is viewed as a binary event by establishing various criteria (e.g., 0, 1, or 2 cm growth over 5 years) and recording the "success" of each tree relative to each of these criteria. A probabilistic model is then fitted which can be used to project diameter distributions through time and account for mortality (trees failing to achieve 0 cm growth) and growth simultaneously. Validation problems unique to these models are discussed as well as methodology to overcome these. A probabilistic model was fitted using data from the Missouri Ozarks and results of this model are discussed.

INTRODUCTION

One method which may be used to model population dynamics is the Leslie Matrix (Leslie, 1945) used in a stochastic process called a Markov chain which has been used to model forest growth and mortality by a number of researchers (e.g., Bruner and Moser, 1973). A simplified forestry example of Markov chain is given in Table 1. Note that all rows sum to 1.00 so that all trees of a given size class at time t are accounted for at t+10 years. To use this model, the percentage of trees in each class at t are moved to the appropriate class at t+10. For example, of the trees in the 20 cm dbh class at t, 67% will be in the same class at t+10, 17% will move up 1 class to 30 cm, 1% will move up 2 classes to 40 cm, and 15% will die.

Table 1. A (theoretical) simplified Markov chain model.

Dbh t	Dbh t + 10 years						
	10	20	30	40	50	60	Mortality
10	0.60	0.13	0	0	0	0	0.27
20		0.67	0.17	0.01	0	0	0.15
30			0.63	0.21	0.08	0	0.08
40				0.60	0.29	0.03	0.08
50					0.75	0.02	0.23
60						0.15	0.85

While this is a useful way to model growth and mortality, this approach has a number of limitations. First, a single site quality is assumed whereas population dynamics vary among sites. Second, a 20 cm tree, for

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example, is treated the same whether the mean diameter of a stand is 10 cm or 50 cm -- i.e., relative size is not quantified. Third, stand structure is ignored meaning that population dynamics are assumed to be the same whether the stand is even or uneven-aged, and/or the stand is pure or of mixed species composition. All of these limitations might be overcome by producing a Markov model for each possible site, stocking, and stand structure combination, but it would be difficult to collect enough data for this approach, and the resulting tables would be unwieldy.

The purpose of this paper is to demonstrate how these limitations can be overcome using logistic regression to produce a single function which is, effectively, a Markov chain model for virtually any combination of stand characteristics.

THEORY

CALIBRATION

In the approach adopted, it is critical to recognize that virtually any event may be viewed as having a binary outcome. In the case of mortality -- a parameter which logistic regression has often been used to model -- the binary outcomes are survival and/or mortality. Growth, however, becomes a binary event after criteria of interest have been established. For diameter, "success" might be defined as 1.0 cm growth over 5 years, and "failure" less than 1.0 cm growth. In the case of failure, the tree "fails" either because of slow growth or mortality. For modeling purposes, however, because a continuum of growth criteria is necessary, a series of criteria are defined.

For example, suppose we have dbh data for 2 trees, a 27 cm tree which has grown 1.2 cm in the last 5 years, and a 15 cm tree which has died during this period. Suppose further that the growth model will be based on 1 cm classes. Success criteria of 0, 1, and 2 cm growth are established to make criteria a continuously-scaled variable for which we record the "success" (1) or "failure" (0) of each tree for each criteria. In our case, the first tree was "successful" for the 0 and 1 cm growth criteria, but not the 2 cm criteria because of slow growth, and the second tree was a "failure" against all 3 criteria because of mortality. Our data would thus appear as follows (with negative growth indicating mortality):

Tree	Dbh	Criteria	Growth	Success
1	27	0.0	1.2	1
1	27	1.0	1.2	1
1	27	2.0	1.2	0
2	15	0.0	-1	0
2	15	1.0	-1	0
2	15	2.0	-1	0

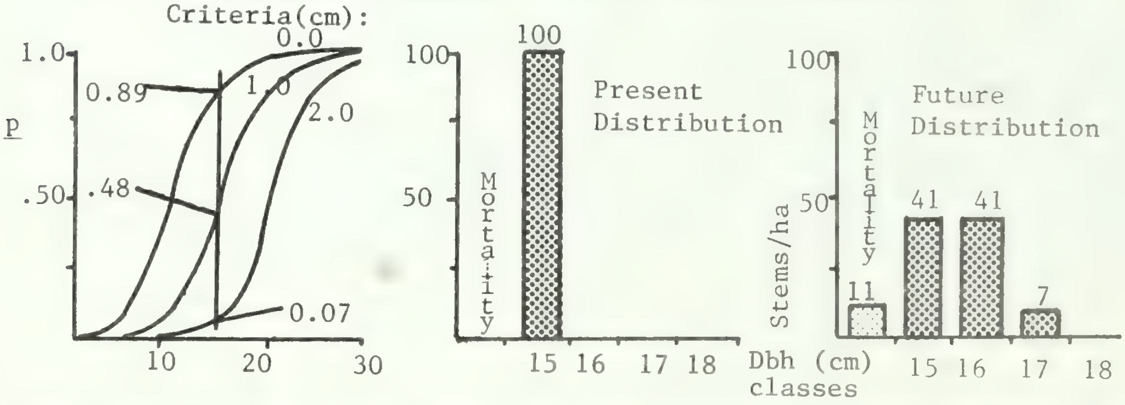
Note that one observation results for each criteria for each tree. After creating this data set, a logistic equation may be fitted by specifying Success as the dependent variable, and using any one of a number of commercially available software packages (e.g., PROC LOGIST from SAS Institute Inc. 1983). Such an equation has the following form:

$$\underline{p} = 1/(1 + \exp(-(b_0 + b_1 \underline{Criteria} + b_2 \underline{Dbh}))) \qquad (1)$$

where p is the probability of a tree of given Dbh being "successful" for a specified Criteria. Equation (1), however, does not circumvent the problems of Markov chains mentioned in relation to Table 1. These limitations may all be overcome, however, by incorporating into equation (1) continuous variables such as site index, a stand density measure, tree dbh relative to stand dbh, crown position, and/or any other variables which relate to tree growth. Note that the way in which mortality is represented in the data is unimportant as the dependent variable is Success and not Growth. Note further that the growth criteria could have been specified as a percent -- i.e. with a 10% growth criteria the 27 cm tree would have had to grow 2.7 cm in 5 years to have been successful. Specifying criteria as a specific dbh, however, has limited utility because, for example, a 10 cm tree has virtually no chance of achieving a dbh of 40 cm in 5 years, just as a 25 cm tree is not likely to be 15 cm dbh 5 years hence.

To use equation (1) for growth modeling, trees in a stand of interest are tallied by 1 cm dbh classes, probabilities generated for all 3 success criteria for each class, and the trees "moved" accordingly (Fig. 1). In this hypothetical situation, 11 trees die ((1.0 - 0.89)*100), 41 survive but do not grow into a larger class ((0.89 - 0.48)*100), 41 move into the 16 cm class ((0.48 - 0.07)*100), and 7 grow into the 17 cm class ((0.07 - 0)*100). This procedure is repeated for each diameter class, and the number of stems, basal area, and volume for each class may be summed for the entire stand and also used to produce estimates of mean diameter and/or stand stocking.

Figure 1. Class movement based on a probability distribution.



Note that though Figure 1a may be viewed as a cumulative frequency distribution for a normal distribution, it is possible to describe other distributions by transforming the independent variables. Further, though the 15 cm class is distributed approximately normally at time t+5 in this particular stand, it can be made to be distributed in other ways by specifying the model differently.

VALIDATION

The validation of logistic models presents a number of problems. For example, equation (1) was fitted using data for single trees, but because it is probabilistic, one cannot simply obtain an independent data set, generate probabilities for each tree, and compare these against actual measured probabilities. Four possible methods to validate probabilistic models are discussed here.

First, the logistic model may to be used to "grow" diameter distributions to obtain estimates of stand parameters for all stands, and these may be compared to measured stand parameters. A limitation to this approach, however, is that errors in each diameter class may compensate making a stand measurement appear accurate and precise though the diameter distribution may not have been estimated well. This suggests a need for testing the distribution themselves.

Second, non-parametric techniques may be used to test if the estimated distribution matches the actual distribution at some future time. In this approach, both distributions are tabulated by diameter classes. Chi-squared might then be used to test for differences in the distributions, but chi-squared is a poor choice if there are less than 5 observations (stems) in a (diameter) class in the expected (actual) distribution as is often the case in modeling forest growth and yield. The Kolmogorov-Smirnov two-sample test assesses differences between distributions and also provides an alternative for validating probabilistic models by testing differences in cumulative frequency between actual and predicted distributions. However, data to fit forest growth models are usually obtained from permanent plots wherein a single tree represents more than one stem per acre -- i.e. 10 stems per acre using 0.10 acre plots. In the K-S test the sample size of the actual and estimated distributions must be known to determine the critical value. In the case of a 0.10 acre plot on which 20 trees exist, it could reasonably be argued that either n=20 or n=200 should be used as the sample size for the actual distribution. Because this selection alone has profound effects on the outcome of this test, the K-S two-sample test is not recommended unless 1 acre plots are measured and/or this problem can be resolved.

Third, the logistic model can be validated by utilizing data from individual trees. After obtaining an independent data set, success probabilities are generated for each tree for each criteria of interest. These are then tabulated by probability classes for each criteria with the number of "successes" and "failures" also tabulated by class. Chi-squared is then used to test for differences in expected and observed "success." The "expected" value is obtained by multiplying a probability class midpoint by the number of observations recorded in the class. The selection of class interval is critical -- a small number of classes provide too few degrees of freedom to make a useful test, and many classes may result in expected values too small to provide meaningful results, particularly in the lower probability classes.

Finally, the logistic model may be validated using a technique that does not rely upon arbitrary class groupings as do the previous three (i.e., 1 cm classes and/or quantiles). After fitting the logistic model, an independent data set is obtained, $\underline{p}$ calculated for each observation using the model, and the logistic model is refitted:

$$\underline{p'} = (1 + \exp(-(b_0 + b_1 \underline{L})))^{-1} \tag{2}$$

where L is ln(p/(1 - p)). In equation (2), if b_0 is equal to 0 and b_1 is equal to 1, then p will equal p' and the model may be considered "valid." Because an estimate of the standard error of each b_i can be produced during the logistic fitting procedure, the t statistic may be used to test each coefficient for significance against the desired value. The validation equation (2) may also be used to plot p' against p to indicate how the calibrated model performs over the range of probability.

EXAMPLE

DATA

The veracity of this methodology was tested using data from University Forest, a 2800 ha forest located in southeastern Missouri in the Ozarks. The area was predominantly agricultural until the 1920s when it was allowed to revert to oak-hickory forest. In 1962, a series of permanent plots were established and have been remeasured every 5 years since that time providing 5 measurements for this study. Plot size depends on tree size with saplings (2.5 - 12.4 cm dbh) measured on 0.004 ha plots, poletimber (12.5 - 27.7 cm dbh) on 0.02 ha plots, and sawtimber (27.8+ cm dbh) on 0.04 ha plots. Dbh, tree height, and crown position were recorded for each tree, and site index for each plot was also determined and recorded. Sixty plots (of 150) were randomly selected -- 30 plots were used for model calibration and validation. (The use of a greater number of plots placed excessive time and memory requirements on the computer used.)

Because of similarities in growth and silvical characteristics, trees were separated into 4 species-groups -- 1)white oaks, 2)red oaks, 3)hickories, and 4)other species. For each 5-year period for which a tree was alive at the beginning, one observation resulted. Thus each tree produced up to 4 records. Each recorded tree dbh at the beginning of the period (t) and dbh 5 years later (t+5) if alive, or a dbh of 0 if the tree died during that time. Each record also contained coded dummy variables to indicate crown position and variables to describe the host stand: mean stand height and diameter, basal area, stems per ha, and stand stocking (Table 1).

Table 1. Summary of calibration data.

	Mean	Standard Deviation	Range
	Plot Characteristics		
Basal area (m^2ha^{-1})	17.1	4.4	4.2 - 27.7
Stems (per ha)	424	120	99 - 642
Stocking (%)	67	16	17 - 105
Mean dbh (cm)	21.9	2.9	17.0 - 35.8
Mean dominant height (m)	19.4	2.9	11.3 - 25.6
	Tree Characteristics		
Dbh (cm)	24.1	8.7	12.7 - 73.4
Height (m)	16.5	4.0	4.5 - 26.5
Dbh growth (cm)	1.3	1.1	0 - 4.6

Note: 34% of stems are white oaks, 48% red oaks, 14% hickory, and 4% other species.

MODEL FITTING

It was first necessary to establish criteria to define "success." Though absolute growth (expressed in cm) was considered, it was found that relative growth (expressed as a % of initial dbh) was more useful. To obtain meaningful models, it was necessary to establish criteria such that a certain proportion of "successes" and "failures" would be present in the data. Approximately 30-70% "successes" were necessary to produce models containing not only the same predictor variables, but also coefficients that did not differ significantly among models. Consequently, 4 growth criteria were established -- 0%, 3%, 7%, and 12% (i.e., 1.0, 1.03, 1.07, and 1.12 of dbh at $\underline{t}$) -- with 4 records resulting from each observation in the previous data set.

Table 2 presents the coefficients of models fitted. Equations are of the form:

$$\underline{p} = 1/(1 + \exp(-(b_0 + b_1*(\underline{CRIT}*\underline{dbh}) + b_2*\underline{dbh} + b_3*\ln(\underline{Reld}/\underline{Stk})))) \quad (3)$$

where $\underline{p}$ is the probability that a tree will grow at least a specified percent 5 years hence, $\underline{CRIT}$ is the predefined growth percent (1.0-1.12 or 0-12% growth), $\underline{dbh}$ is present tree dbh (cm), $\underline{RelD}$ is present tree dbh divided by mean plot dbh, and $\underline{Stk}$ is stand stocking (%). To help overcome the serial correlation in the data, a relatively stringent significance level (0.001) was adopted for variable inclusion. Though the variable associated with b_3 may not make intuitive sense, it quantifies a difference in growth potential wherein a relatively large tree ($\underline{RelD} > 1.0$) will result in little growth if the stand is overstocked, though such a tree will grow more than a smaller tree ($\underline{RelD} < 1.0$) under the same conditions.

Table 2. Logistic regression coefficients for estimating the probability that a tree will attain a specified growth percent over a 5-year period.

Species Group	Regression Coefficients				1/	2/
	b_0	b_1	b_2	b_3	FCP	RC
White oaks	8.901	-2.711	2.733	1.594	0.916	0.837
Red oaks	13.23	-2.212	2.233	2.508	0.925	0.854
Hickories	8.765	-4.425	4.402	1.419	0.940	0.885
Other	-1.289	-2.385	2.498	0.000	0.906	0.817

1/Fraction of concordant pairs of predicted probabilities and responses.
2/ Rank correlation between predicted probability and response.

RESULTS AND DISCUSSION

Table 3 was produced by generating $\underline{p}$ for each tree observation in the validation set for a given criteria, stratifying these by deciles centered upon 0.05, 0.15, etc., and calculating and testing the chi-squared value as explained earlier. For individual trees, values were only significant at $\underline{p} < 0.05$ in 2 cases -- 8% of the cells -- and one of these was for hickory, a relatively minor component of the validation data.

Table 3. Results of chi-squared tests for significance of differences between observed and expected growth.

Species	Criteria: Growth Percent						No.
Group	0	3	6	9	12	15	stems
White oaks			*				330
Red oaks							519
Hickories		**					111
Other							65

* - significantly different from zero (5%)
** - significantly different from zero (1%)

Though the results in Table 3 indicate that distributions appear to be projected through time adequately, model users may be more concerned with stand characteristics. Models were used to "grow" the 1962 distribution for each plot in the validation data to 1982 by 5-year steps. Stand statistics were then derived from the distributions, and residuals calculated (observed - estimated) and summarized for all 30 plots (Table 4).

Table 4. Validation of plot estimates for 30 plots.

Meas.	Basal area(m^2/ha)			Stems per ha			Mean dbh (cm)		
Period	MR	SE	PI	MR	SE	PI	MR	SE	PI
1962-1967	0.71*	0.31	3.5	14.9*	5.9	67.2	0.15	0.16	1.8
1962-1972	0.64	0.58	6.5	16.7	11.6	132.1	-0.03	0.29	3.3
1962-1977	-0.32	0.83	9.4	-14.2	17.1	194.7	0.63	0.68	7.7
1962-1982	-0.79	0.95	10.8	-26.2	16.9	192.4	0.56	1.03	11.7

MR - Mean residual SE - Standard error
PI - Prediction interval -- 95% range (centered on the mean residual) of the expected residual from a single use of the model
* - significantly different from zero (95%) as measured by t

Though precision tends to deteriorate over time, the absolute value of the mean residual does not tend to increase. The sign of the mean residual also changes indicating further that the model will not produce biased estimates of stand parameters. While estimates of stems per ha appear poor, it must be remembered that this model (and many others) predicts mortality as a general trend whereas the data represent it as an event occurring at one point in time. In the validation data, most mortality occurred between 1972 and 1977. Compounding the problem is the small size of remeasurement plots wherein a single tree death indicates as many as 250 saplings dying in a particular period.

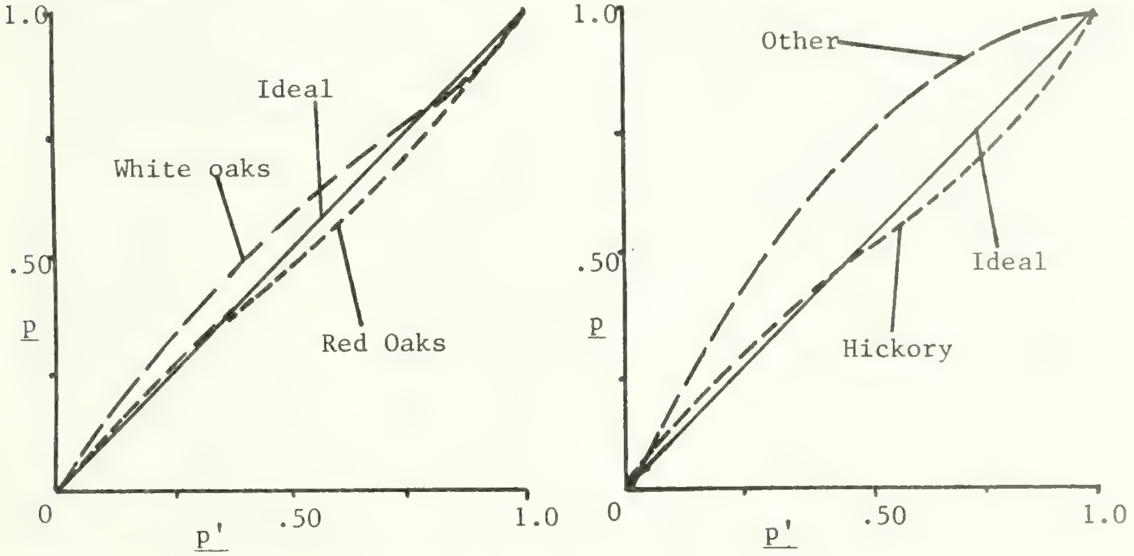
Validation was also undertaken by comparing the predicted probability, p, to the observed probability, p' for the validation data set, and testing b_0 and b_1 for equality with 0 and 1, respectively, as explained earlier (Table 5). The models are not ideal with many coefficients significantly different from their hypothesized value. Graphs of p against p' (Figure 2) indicate areas of discrepancy. For example, the misestimation of b_0 for "other" causes p to be overestimated resulting in greater survival and growth predicted than actually occurs. Conversely, hickory suffers much less misestimation, and red oak is estimated reasonably well over the range of probability.

Apparently, the models (Table 2) could be improved despite their seeming adequacy based on other validation techniques. One possible improvement

Table 5. Coefficients for equation (2) and significance.

Coefficients	White Oaks	Red Oaks	Hickories	Other
b_0	0.27**	-0.09	-0.05	0.92**
b_1	0.85**	0.91*	0.73**	1.23

Figure 2. Predicted (p) against observed (p') probability. (Solid line is ideal relationship -- i.e. $b_0 = 0$ and $b_1 = 1$.)



could be the incorporation of a site quality variable, though such a variable was not found to be a significant predictor of "success" here. Crown position was found to be a significant predictor but its use requires the derivation of additional functions to estimate whether a tree of given diameter is at least codominant. An additional future improvement could be the incorporation of the prediction (time) interval into equation (3) so that, for example, a 15-year prediction would not require three 5-year "stops."

CONCLUSIONS

Logistic regression shows promise for producing a single function to estimate growth and mortality simultaneously by projecting diameter distributions through time. Validation of logistic models presents unique problems, though there are ways to overcome these. The example discussed herein demonstrates the utility of this approach, though improvements and refinements in the technique need to be made.

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NEAREST NEIGHBOR INFERENCE FOR CORRELATED MULTIVARIATE ATTRIBUTES

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ABSTRACT. A new multivariate inference procedure for use with a two-phase sample assigns dependent variable values from the most similar ("nearest neighbor") second-phase sample unit to a given first-phase unit. Nearest neighbor selection is by a minimum distance function using weights derived from a canonical correlation analysis between the dependent and independent variables in the second-phase sample. Compared to estimates for multivariate yield variables derived from linear regression, nearest neighbor inference reproduces the covariance structure of the observed data. Further, the procedure retains the full range of variability inherent in the sample. Also, nearest neighbor estimates are nearly as efficient as regression estimates for easy-to-predict dependent variables. These characteristics should make nearest neighbor a practical inference procedure when it is important to preserve the relationships among dependent variables -- for example, when models designed to predict responses of several variables simultaneously are driven using sample unit data as input.

INTRODUCTION

Resource planning commonly requires information about every single unit of land in a planning area. While measures of yield variables are usually prohibitively expensive to obtain for every land unit, yield estimates can be made from their relationships with auxiliary variables, which are more easily or cheaply measured as part of a multiphase inventory. In two-phase sampling, for example, a vector of independent variables, $\underline{X}$, is measured on all units constituting the population, and a vector of dependent variables, $\underline{Y}$, correlated with $\underline{X}$, need only be measured on a subsample of units.

The usual inference methodology associated with two-phase sampling assigns to each unit in the population an average value for each element of $\underline{Y}$ derived from the second-phase sample. In natural resource planning, these averages are often stratum means or regression estimates. However, in evaluating inference procedures to be used in a planning context, the role of variation and covariation between yield variables should be considered in addition to estimation of population means or totals. In a forestry example, an exceptionally high-volume stand of trees with an exceptionally low erosion hazard would play a key role in a management objective for producing timber with minimum impact on a fishery. In many cases, the ability to preserve the relationships between yield variables

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and to estimate extreme values may be more useful to meet the objectives of management than is the ability to compute yield averages. Therefore, yield estimates obtained by sampling inference should be subject to two new criteria: first, to retain the full range of sample variation, and second, to exhibit the same correlation structure as characterize the population for which the plan is being prepared.

A new sampling inference procedure proposed here (termed "nearest neighbor") selects only one unit from the second-phase sample to be used as a surrogate for a given first-phase sample unit. In this respect, the procedure is analogous to stratified sampling with a single sample unit per stratum. It differs in its particular method for determining stratum boundaries and estimating error. In the procedure, estimates of the dependent variables for each unit in the first-phase sample are simply the measured values of the dependent variables for the surrogate sample unit. The surrogate (or "nearest neighbor") is selected by virtue of being most similar to the first-phase sample unit, in a combination of characteristics simultaneously.

Similarity is measured by a distance function that incorporates the multivariate relationship between $\underline{X}$ and $\underline{Y}$ in the second-phase sample. Interest in predicting $\underline{Y}$ for first-phase sample units suggests that a surrogate should be selected based on its having similar values for all elements of $\underline{Y}$. The nearest neighbor distance measure is a quadratic form in the difference between the sample unit to be assigned, and its potential surrogates, with weights derived from canonical correlation analysis. The surrogate units are represented by a (1xp) vector of predictor variables, $\underline{X}_j$, and a (1xq) row vector of yields, $\underline{Y}_j$. Let the unit to be assigned have a predictor vector, $\underline{X}_0$. The nearest neighbor distance formulation is:

$$D^2_{0,j} = (\underline{X}_0 - \underline{X}_j)\ \Gamma\ \Lambda^2\ \Gamma'\ (\underline{X}_0 - \underline{X}_j)'$$

where

Γ = matrix of canonical coefficients of the predictors, $\underline{X}$, and
Λ^2 = diagonal matrix of squared canonical correlations between $\underline{X}$ and $\underline{Y}$ in the second-phase sample units.

Then, the search for a nearest neighbor for first-phase sample unit 0 is to find the jth second-phase sample unit with minimum distance, $D^2_{0,j}$. The role of the weighting matrix, $(\Gamma\Lambda^2\Gamma')$, is two-fold. First, it scales elements of $\underline{X}$ according to their relative predictive power for all the yield variables simultaneously. In contrast, regression results in a separate linear combination of $\underline{X}$ for each element of $\underline{Y}$, making the approach essentially univariate. Second, it incorporates an estimate of covariance among the yield variables. This prevents the distance measure from being dominated by a few highly predictable elements of $\underline{Y}$ at the expense of less predictable elements of $\underline{Y}$. For an excellent discussion of theory and other applications of canonical correlation analysis, see Gittins (1985).

EXAMPLE

DATA

Multivariate forest inventory data were used to test the nearest neighbor procedure and to compare its performance to univariate linear regression. The data were from 236 stands measured during an inventory of forested lands in the state of Montana, USA (Martin et al., 1983). The phase-one (or independent) variables were recorded from stand records, maps and aerial photographs, while the second-phase (or dependent) variables were stand yield characteristics measured on the ground. Martin et al. (1983) developed univariate regression equations to predict the ground attributes from combinations of the photo variables. In the present analysis, nearest neighbor inference was used on the same data to simultaneously estimate 11 different ground variables (e.g., volume, growth, site index, and basal area) based on their minimum-distance surrogates. The distance function used 28 predictor variables observed on the aerial photos and maps (e.g., crown size, canopy cover, stand height, slope, aspect, and elevation).

ANALYSES

For each sample unit in the data, predicted values for each of the 11 dependent variables measured in the inventory were estimated using nearest neighbor and regression procedures. The following analyses were done:

1) The two methods were compared for how well they reproduce the multivariate structure of the observed data, with emphasis on the relationships among dependent variables. This evaluation was by graphical comparison of the joint distributions of predicted variables to the observed distributions.

2) How well the two methods retain the inherent variability of the observed data was evaluated by graphically comparing the univariate distributions of the estimates to their observed distributions. Particular attention was paid to the ranges of predictions to note whether extreme values which occurred in the sample were duplicated in the predictions.

3) The difference between the mean predicted by each method and the observed mean was tested using a paired t-test, and the magnitude of the standard error of the residuals (observed - predicted) from each method for each dependent variable was compared. In addition, the "fit" of the nearest neighbor and regression estimates was evaluated by comparing scatterplots of observed versus predicted values, and residuals versus predicted values.

RESULTS

Figure 1 shows the joint distribution of 2 of the 11 dependent variables (cubic foot volume and growth) for the observed data, nearest neighbor estimates, and regression estimates. Clearly, the relationship between these variables in the nearest neighbor predictions is similar to the observed data. The relationship is reproduced only poorly by the regression predictions.

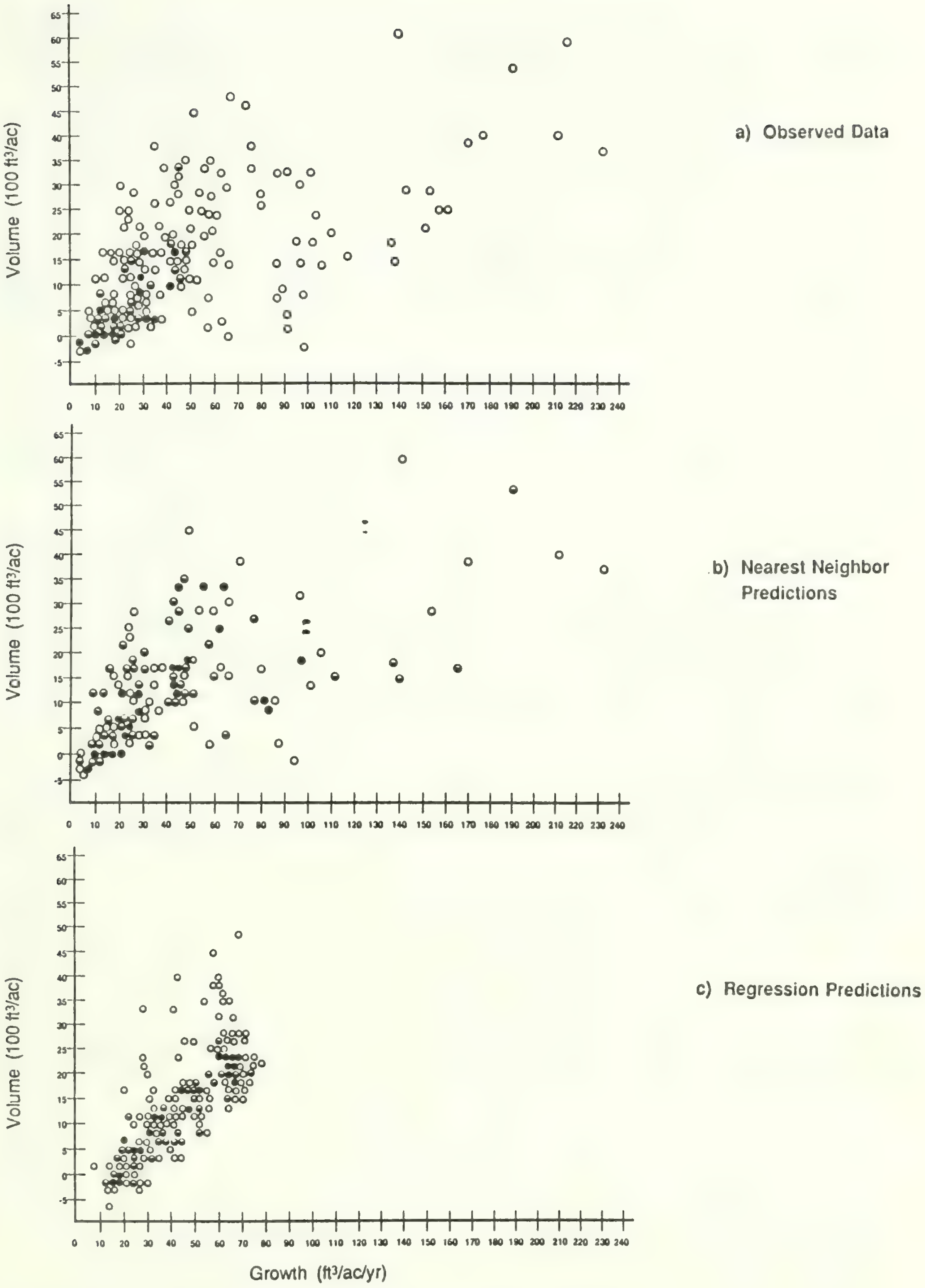

Figure 1. Joint distribution of volume and growth.

The simultaneous estimates derived from nearest neighbor inference reproduce the original correlation structure among the dependent variables, regardless of their joint distributions. Regression, on the other hand, is much more sensitive to departures from multivariate non-normality. Regression results in least-squares estimates for variables such as volume and growth individually, but does not preserve the correlations between them unless they have a joint normal distribution. Fisher's test (1921) for correlations emphasizes this result. Of 55 possible pairs of correlations between the 11 dependent variables, only three nearest neighbor dependent variable predictions were significantly different from the paired correlations in the observed data. All but 7 correlations were significantly different from the observed data in the regression results.

Univariate distributions for the nearest neighbor predictions were more similar to the observed distributions than were the regression predictions for every dependent variable in the analysis. The ranges of nearest neighbor predictions were nearly identical to the observed ranges for all 11 variables (Table 1). In regression, the span of predicted values is more sensitive to model form and departures from distributional assumptions. For example, if the correlation between a dependent variable and its predicted values is low (as for growth), the regression estimates, because of near-zero slope, show little variation about the mean. Also, predictions outside the range of data used to fit the regression may result in unreasonable estimates if the model is misspecified. Notice that regression produced negative predicted values for volume and growth. Nearest neighbor predictions can only span the range of the original data (making illogical negative predictions impossible) and do span that range quite thoroughly, at least for these data.

TABLE 1. Comparison of nearest neighbor and regression predictions to observed values. Mean ($\bar{Y}$), range (Min and Max), and standard error ($SE_{\bar{Y}}$).

Dependent variable	Observed values				Nearest neighbor predictions				Regression predictions			
	$\bar{Y}$	Min	Max	$SE_{\bar{Y}}$	$\bar{Y}$	Min	Max	$SE_{\bar{Y}}$	$\bar{Y}$	Min	Max	$SE_{\bar{Y}}$
Volume (bfs/ac)	5084	123	25084	278.2	5047	123	25084	102.1	5087	-1546	24323	67.0
Volume (bfi/ac)	6114	169	28894	324.5	6094	169	28894	119.2	6116	-1899	28409	79.5
Volume (ft^3/ac)	1692	57	6256	78.5	1649	57	6256	49.8	1698	-283	5204	43.0
Growth (bfs/ac/yr)	129	5	628	7.3	125	7	628	7.2	129	-19	278	6.5
Growth (bfi/ac/yr)	148	6	712	8.5	142	7	712	8.7	148	-14	314	7.7
Growth (ft^3/ac/yr)	43	1	234	2.7	42	2	234	3.5	43	8	72	2.6
Yield (ft^3/ac/yr)	72	29	141	1.6	73	29	141	1.8	72	44	126	1.3
Site Index (50 yr)	56	17	109	0.8	56	17	83	1.0	56	44	79	0.8
Stocking (%/ac)	84	7	158	2.0	83	10	152	2.6	84	40	122	1.7
CCF	133	52	554	4.3	134	52	554	5.2	133	54	213	3.7
Basal Area (ft^2/ac)	87	4	295	3.3	85	4	295	2.9	86	7	160	2.3

In paired t-tests between observed and predicted means, no differences were significant for any dependent variable for nearest neighbor or regression estimates ($p = 0.05$). Nearest neighbor estimates for the 11 dependent variables differed in absolute value from the observed means by 4% or less, while the regression estimates differed by 0.3% or less.

The standard errors of the nearest neighbor estimates were between 2% and 8% of the predicted mean, and between 1% and 6% for regression. Nearest neighbor estimates for variables that were easy to predict (e.g., volume) were almost as efficient as for regression (standard errors within 3% of the mean). The ranking of standard errors for the nearest neighbor estimates generally reflected that of regression; i.e., when the regression models produced a "good" fit, then the nearest neighbor relationships were also good.

Among the 11 dependent variables, two typical patterns of predictions emerged (shown for cubic foot volume and growth in Figure 2). If a variable was linearly related to its predictors (e.g., volume), it was predicted nearly equally well by nearest neighbor or regression analysis. For these variables, both regression and nearest neighbor predictions were highly correlated with observed values (r-squared greater than 0.9), and both procedures produced independently distributed residuals. The second pattern was indicative of hard-to-predict variables, such as growth. For these variables, both nearest neighbor and regression procedures produced heteroscedastic residual patterns.

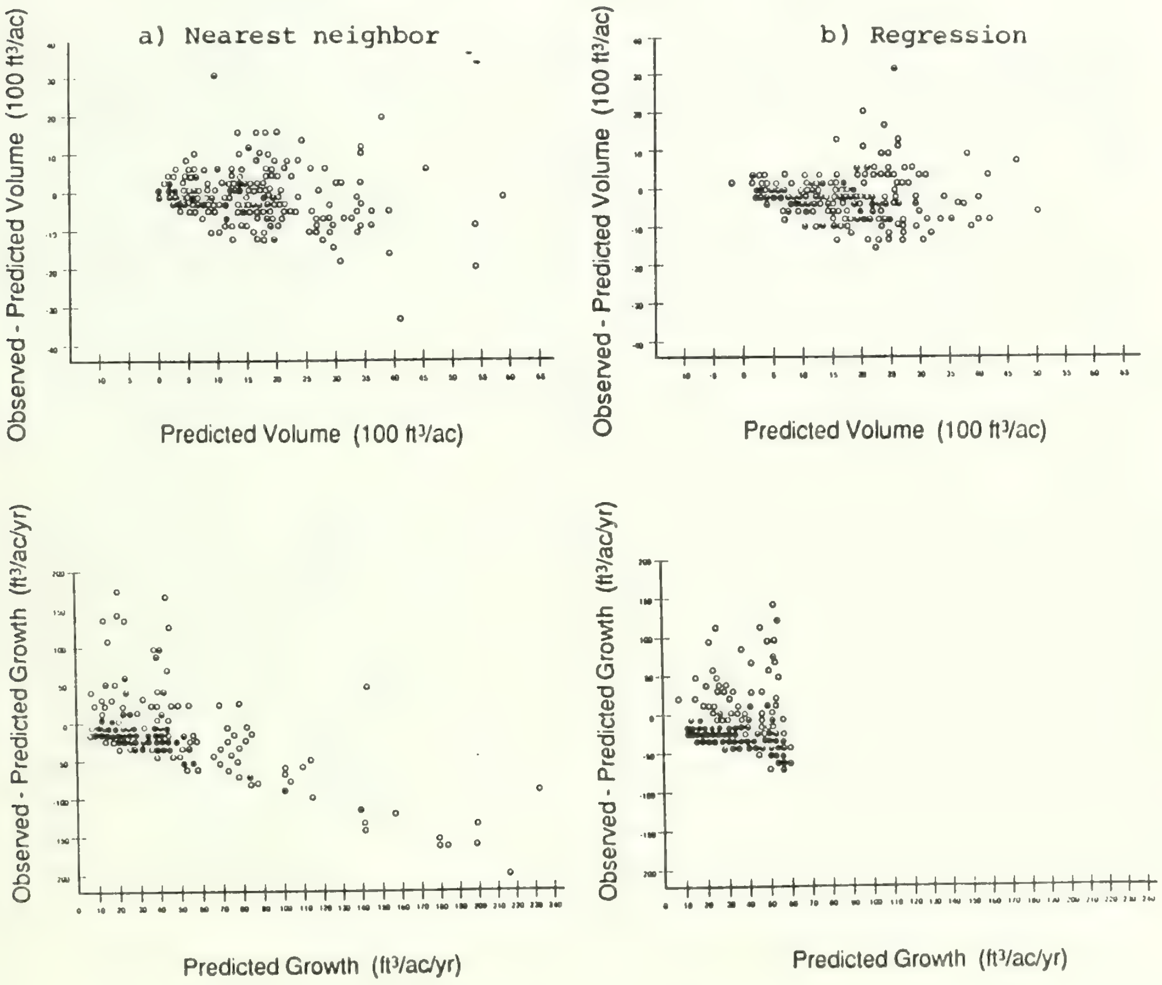

Figure 2. Residuals (observed - predicted) vs. predicted values for volume and growth.

If evaluating these methods purely upon their performance in estimating individual dependent variables, then either is appropriately applied to easy-to-predict variables such as volume, but both nearest neighbor and regression are inappropriate models for hard-to-predict variables such as growth. Regression will produce a least-squares estimate for hard-to-predict variables, but will do so by constraining the range of predicted values. Regression estimates will not extrapolate well, and will not be inherently tied to variables which do predict well. Nearest neighbor would be equally inappropriate for estimating individual hard-to-predict variables. However, extreme predictions for such variables should be realistic because their relationship to more predictable variables has been preserved.

CONCLUSIONS

The nearest neighbor and regression estimates both have standard errors within 3% of the mean for yield variables with well-defined linear relationships with their respective covariates. Thus, nearest neighbor inference should perform as well as regression in sampling contexts requiring estimates of population means or totals for these variables. At the same time, nearest neighbor inference results in predicted values for correlated dependent attributes that reflect the observed covariance structure better than regression does. For a variable not highly linearly related to its covariates, regression distorts the relationship by constraining it to be linear, while nearest neighbor retains the inherent covariance structure. Retaining these correlations is in large part due to the novel use made of canonical correlation analysis. Canonical analysis commonly has been used to predict one set of variables from another. Results of such applications have been disappointing because the linearity of the solution is usually unrealistic for ecological data. Nearest neighbor results are much less sensitive to nonlinearities, because in this context canonical analysis is used to calculate weights for the distance measure rather than to make actual predictions for individual variables.

Impossible predictions cannot occur in nearest neighbor sampling as they can in regression. In regression, the span of predicted values may be influenced by two occurrences. First, predictions outside the range of data used to fit the regression may not extrapolate well if the specified model form is wrong. Second, if the linear relationship between y and $\underline{X}$ is poor, the resulting regression line will be rather flat, producing a limited range of predicted responses. Nearest neighbor predictions span the range of the observed data as well as retain the natural variability of that data. A possible disadvantage to using nearest neighbor inference is that the most extreme prediction is limited to the most extreme observation in the original sample. Because the procedure will not extrapolate values outside the range of the data, it is important that the sample adequately represent the population of interest.

Conventional procedures produce estimates that are aggregates of the sample data. For example, in simple random sampling, the mean of a dependent variable tabulated over a sample is imputed to every unit in the population, resulting in a high degree of aggregation of sample information. In stratified random sampling, aggregation is dispersed to the stratum level. Every unsampled unit within a stratum will be assigned the same estimate for a given dependent variable. A univariate regression model will further decrease the level of aggregation because the regression estimate represents a "moving" mean.

Compared to the other procedures, nearest neighbor inference results in the lowest degree of aggregation because it is analogous to stratified sampling with a single sample unit per stratum. The error sum of squares that is accounted for in regression is deliberately retained in nearest neighbor. This result has practical advantage in some contexts, as when applied in planning models using constrained optimization procedures. Deliberately retaining variability of yield estimates may result in a higher value of the objective function simply by presenting more choices in the solution.

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MIXED LINEAR MODELS FOR STEM SIZE AND FORM DEVELOPMENT

Risto Ojansuu[1]

Abstract. Mixed linear models are used to model the growth of tree size and changes in stem form. The stem is defined in polar coordinate system as the logaritmic lengths of rays at different angles. The error variance in the model has been divided into between-plot and within-plot components, and these in turn have been divided further into the components caused by prediction error of stem size growth and of stem form development. The between-plot errors among different parts of the stem are strongly correlated and about 90% of the variation is caused by the stem size growth prediction error. The corresponding within-plot errors are weakly correlated, and about 50% of the variation is caused by stem size growth prediction error.

INTRODUCTION

In individual tree based stand growth simulators, the diameter at breast height and tree height are the most commonly used dynamic tree variables (see e.g. Ek and Dudeck 1980). Other characteristics of the tree are obtained as a function of these dynamic tree variables by using static tree models. Some stand growth simulators have also been development, which simulate stem form development (e.g. Arney 1974 and Hegyi 1974).

Sloboda (1977) has studied stem form development with a curvlinear polar coordinate system. This paper presents an alternative approach to analyse stem form development using polar coordinates and presents some preliminary results. The approach was originally developed to analyse static form variation by Lappi (1986). Lappi's model is based on the mixed linear models methodology, where the error variance was divided to between-plot and within-plot component. In this adaption the variance is also divided into the parts caused errors in stem size growth prediction and errors in stem form development prediction.

TREE STEM MODEL

The polar coordinate system is used in this study to define the position of the points of the tree stem. The dimensions of the tree can be expressed as the length of the rays, $R(u)$, where u is the angle. The fixed angles used in the model are

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0.25°, 1.5°, 5°, 14°, 31°, 56° and 90°. The ray length at angle 0° is equal to the diameter at the base of the stem, and the ray lengh at angle 90° is the stem height. The coordinate systems units are cm for the horizontal axis and m for the vertical axis.

Stem size is defined as the weighted mean of the logarithms of the rays at the seven fixed angles (Eq. 1).

$$s_{ki} = \sum_{u=1}^{7} w(u) \cdot r_{ki}(u) \tag{1}$$

where s_{ki} is the logarithmic size of tree i on plot k, $w(u)$ is the weight at angle u, and $r_{ki}(u)$ is the logarithmic length of the ray of tree i on plot k at angle u. The weights are definit the first characteristic vector of the covariance matrix respecting ray lengths of the whole data, scaled in such a way that the sum of the weights is 1, i.e. $w = (.1591, .1500, .1492, .1475, .1407, .1312, .1223)$,

The growth model consists of seven regression models of equal structure one for each fixed angle. The factors affecting tree growth are divided into three components: 1) the site type on plot k (H_k), 2) the state of tree i on plot k (F_{ki}), and the competition measure of tree i on plot k (C_{ki}). Here the growth factors are assumed to have a multiplicative effect and that no interactive effects occur. Then the model for relative growth can be written in form

$$R_{ki}^{+}(u)/R_{ki}(u) = H_k \cdot F_{ki} \cdot C_{ki} \cdot E_{ki}(u) \tag{2}$$

where $R_{ki}(u)$ is the ray length of tree i on plot k at angle u , $R_{ki}^{+}(u)$ is the length of the same ray one year later and, $E_{ki}(u)$ is the corresponding error term.

Natural logarithms are taken in equation (3), and the logarithmic variables are denoted by lower case letters:

$$r_{ki}^{+}(u) - r_{ki}(u) = \rho r_{ki}(u) = \mathrm{Ln}(H_k) + \mathrm{Ln}(F_{ki}) + \mathrm{Ln}(C_{ki}) + \epsilon_{ki}(u) \tag{3}$$

In the model, the prediction error $\epsilon_{ki}(u)$ is divided into between-plot $v_k(u)$ and within-plot $e_{ki}(u)$ components (Equ. 4). The components are independent of each other, and the expected value of both is 0:

$$\rho r_{ki}(u) = \mathrm{Ln}(H_k) + \mathrm{Ln}(F_{ki}) + \mathrm{Ln}(C_{ki}) + v_k(u) + e_{ki}(u) \tag{4}$$

In the growth model, the terms $v_k(u)$ and $e_{ki}(u)$ can be divided into the prediction errors of the change in stem size and the change in stem form. The prediction errors of the stem size v_k^s and e_{ki}^s are calculated using the definition of stem size

$$v_k^s = \sum_{u=1}^{7} w(u) \cdot v_k(u) \quad \text{and} \quad e_{ki}^s = \sum_{u=1}^{7} w(u) \cdot e_{ki}(u) \tag{5}$$

where the weight vector w is the same as in equation (1). The prediction errors of the stem form change $v_k^m(u)$ and $e_{ki}^m(u)$ are defined as

$$v_k^m(u) = v_k(u) - v_k^s \quad \text{and} \quad e_{ki}^m(u) = e_{ki}(u) - e_{ki}^s \tag{6}$$

The weighted sum of $v_k^m(u)$ and $e_{ki}^m(u)$ are 0 for every plot and tree. In contrast, v_k^s and e_{ki}^s usually deviat from 0, the deviations depicting the magnitude of the prediction error in size growth of the plot or the stem.

MATERIAL

The material in the model presented is a set of 133 sample plots measured in artificially regenerated Scots pine (Pinus sylvestris L.) stands by Vuokila and Väliaho (1980). Annual stem diameter growth had been measured at 10 relative heights and the height growth in five years periods. In this study annual height growth is assumed to remain constant within each five-year period. The annual rays at the fixed angles have been interpolated by cubic splines from the diameters measured.

Some of the sample plots had to be rejected due to incomplete measurements of diameter growth. The final material consisted of 830 pines, for an average of 6.3 pines per sample plot. Only one growth period from each sample plot was used in the analysis.

RESULTS

The site variables used in the model are the effective temperature sum (ETS, d.d.), altitude (ALT, m), and forest site type according to Cajander (1926) (FST). The tree state variable used is tree size, s, and the competition variables are stand density, SS, and the relative tree size, $sdom_k - s_{ki}$, where $sdom_k$ is the logarithm of the dominant tree size on plot k. The natural logarithm of the dependent variables are denoted by lower case letters. The overall form of the basic model is

$$\begin{aligned} \rho r_{ki}(u) = {} & \beta_0 + \beta_1 ets_k + \beta_2 (ALT_k/100) + \beta_3 s_{ki} + \beta_4 ss_k + \\ & \beta_5 (sdom_k - s_{ki}) + v_k(u) + e_{ki}(u) \end{aligned} \tag{7}$$

where β_0 is a dummy variable according to the forest site type. Sample plot density is defined according to the following formula:

$$SS_k = \sum_{i=1}^{n_k} (\exp(s_{ki}))/area_k \tag{8}$$

where n_k is the total number of trees on plot k, and $area_k$ is the area of plot k in hectars.

Model parameters have been estimated by using a mixed linear model technique. The sample plot was a random factor. The parameter values are given in Table 1.

TABLE 1. Estimates of the parameters β_0, β_1, β_2, β_3, β_4 and β_5 for the model (7) at fixed angles u and for size growth, s. The constant for fertile sites is β_{0mt}, for intermediate sites β_{0vt}, and for poor sites β_{0ct}.

parameter	u							s
	1	2	3	4	5	6	7	
β_{0mt}	-.07277	-.10071	-.10942	-.11108	-.09284	-.07918	-.07918	-.09320
β_{0vt}	-.07541	-.10223	-.11129	-.11210	-.10284	-.08049	-.08429	-.09453
β_{0ct}	-.07417	-.10158	-.11021	-.11054	-.09300	-.07944	-.08417	-.09372
β_1	.01974	.02067	.02133	.01827	.01498	.01186	.01118	.01714
β_2	.00254	.00244	.00273	.00311	.00352	.00362	.00232	.00288
β_3	-.01682	-.01312	-.01441	-.01362	-.01610	-.02076	-.02270	-.01656
β_4	-.00053	.00038	.00117	.00335	.00460	.00695	.00896	.00329
β_5	-.01261	-.01126	-.01143	-.01166	-.01480	.01534	-.01281	-.01278

The parameters of the stem size growth model $\beta_l(u)$ that correspond to the estimated stem growth model are calculated by

$$\beta_l(s) = \sum_{u=1}^{7} w(u)\cdot\beta_l(u) \tag{9}$$

in which l denotes the rank number of the parameters, presented in the last column.

The fitting constant method has been used to calculate within-plot and between-plot residual variances (see Searle 1971). The covariance matrices of the prediction errors of the different fixed angles have been calculated using the formula

$$Cov(x,y) = 0.5\cdot(Var(x+y) - Var(x) - Var(y)) \tag{10}$$

(see Lappi 1986). The between-plot and within-plot variances are, on average, of the same order of magnitude (Table 2). The between-plot variance at the stem base is lower and that in the crown part is higher than the within-plot variance. The correlations of the between-plot prediction errors are also strong between the base and the upper part of the stem. The correlations between adjacent angles within-plot are relatively high, but the correlation coefficients rapidly decrease with increasing distance between the angles.

TABLE 2. Estimates of between-plot and within-plot standard deviations and correlations for the basic model (Eq. 7). The diagonal elements are standard deviations multiplyed by 100 and the off diagonal elements are correlations.

	Between-plot							Within-plot						
u	1	2	3	4	5	6	7	1	2	3	4	5	6	7
1	.50							.64						
2	.96	.45						.51	.47					
3	.97	.99	.44					.61	.73	.47				
4	.90	.97	.98	.50				.54	.65	.68	.46			
5	.85	.92	.94	.99	.58			.41	.55	.55	.56	.48		
6	.78	.85	.88	.92	.95	.63		.23	.36	.35	.38	.54	.52	
7	.71	.79	.70	.85	.91	.89	.64	.03	.13	.12	.14	.28	.32	.46

The major portion of between-plot error variance is due to v_k^s. On the other hand, about one half of the within-plot error variance is due to $e_{ki}^m(u)$, and in the height growth (u=7) almost all of it (Table 3). The prediction errors of the size growth and form development may be correlated. The proportion of the $e_{ki}^m(7)$ over 100% indicates, however, clear negative correlation between the terms e_{ki}^s and $e_{ki}^m(7)$.

TABLE 3. The relative amount of the variances between-plot ,$V(v)$, and within-plot ,$V(e)$, caused by the prediction errors in stem form development total, in percent.

	u						
	1	2	3	4	5	6	7
$V(v)$	14.8	7.8	7.8	1.8	4.3	12.1	19.5
$V(e)$	49.4	35.5	34.5	39.9	39.9	61.8	104.1

The ability of additional variables to improve the model was studied by adding variables to the model (7). The mean stem form of a plot was tested as an independent variable by adding the three first principal components, M_k^j, j=1, 2, 3, of the plot average logarithmic rays at the fixed angles as independent variables to the model.

$$\rho r_{ki}(u) = \beta_0+\beta_1 ets_k+\beta_2(ALT_k/100)+\beta_3 s_{ki}+\beta_4 ss_k+\beta_5(sdom_k-s_{ki})+ \\ \beta_6 M_k^1+\beta_7 M_k^2+\beta_8 M_k^3+v_k(u)+e_{ki}(u) \tag{11}$$

The effect of logaritmic tree age ,a, as the independent variable was calculated by

$$\rho r_{ki}(u) = \beta_0+\beta_1 ets_k+\beta_2(ALT_k/100)+\beta_3 s_{ki}+\beta_4 ss_k+\beta_5(sdom_k-s_{ki})+ \\ \beta_6 a_{ki}+v_k(u)+e_{ki}(u) \tag{12}$$

Also simultaneous addition of both factors to the model was tested:

$$\rho r_{ki}(u) = \beta_0+\beta_1 ets_k+\beta_2(ALT_k/100)+\beta_3 s_{ki}+\beta_4 ss_k+\beta_5(sdom_k-s_{ki})+ \beta_6 M_k^1+\beta_7 M_k^2+\beta_8 M_k^3+\beta_9 a_{ki}+v_k(u)+e_{ki}(u) \tag{13}$$

On the average, the mean stem form (Eq.11) and the tree age (Eq.12) explain the variation between the sample plots equally well (Table 5). Of those two equations, stem form better explains the growth at the base of the stem, while tree age better explains height growth. Simultaneous inclusion of both factors in the model decreases the variance between the sample plots even more significantly, especially in the upper part of the stem. Within-plot error variance is not decreased when the above dependent variables are included because the form parameter only depicts the variation between sample plots, and tree age hardly varies within artificially regenerated stands.

TABLE 5. Between-plot error variances at different angles in models (7), (11), (12) and (13).

				u			
Model	1	2	3	4	5	6	7
(7)	.286	.303	.289	.298	.316	.304	.266
(11)	.242	.244	.233	.221	.234	.213	.192
(12)	.251	.254	.232	.229	.223	.207	.177
(13)	.236	.231	.219	.199	.196	.171	.151

DISCUSSION

The main emphasis in this paper is on the analysis of stem growth model prediction errors (Eq.7). The within-plot and between-plot error variances in the basic model are, on average, of the same order of magnitudel. The error terms can be reduced by including independent variables with better explanatory ability or using some a priori information on growth. The site and stand variables have a direct impact on the between-plot error terms. The mean stem form depicted by the three first principal components decreased between-plot variances about 30%. Those variables which have variation within-plots can have an influence on the between-plot errors.

To reduce within-plot errors one can only use those variables that have within-plot variation, like tree variables or different kind of distance-independent or distance-dependent competition variables. The use of tree age reduced only the between-plot variance because tree age does not vary within plots on artificial regenerated stands. In mixed age stands, it could also have an effect on within-stand variation. By including more detailed competition variables to the model, the error variances would not be significanly reduced (s.e. Martin 1978).

The use of the a priori information on stem growth in one stem dimension is based on the correlations between the prediction errors at different angles (see Lappi 1986). Plot level a priori information on growth in one dimension could be used very effectively to reduce the error variance of all other dimensions and size growth, because the between-plot errors at different angles are strongly positively correlated and 80-98% of the variances are caused by errors in size growth prediction. A valuable source of a priori information could be site index curves, because the dominant height development is a relatively stable function of stand age.

More profound analysis of the error term could be done by analysing the time series structure of the between-plot and within-plot prediction errors, as well as the errors when predicting size growth and form development.

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SOME IMPLICATIONS OF THE ALGEBRAIC DIFFERENCE APPROACH FOR DEVELOPING GROWTH MODELS

Hugo Ramirez-Maldonado, Robert L. Bailey
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ABSTRACT. Most forest growth and yield models are based on a functional relationship between a size variable (volume,basal area, height, etc.) and age. For example, consider the height-age models:

$$H = \alpha \exp\{-\beta/A\} \qquad \text{(Schumacher 1939)}$$

and $$H = \alpha\{1 - \exp[-\beta A^{\gamma}]\}^{\lambda} \qquad \text{(Bailey 1980),}$$

where H is height, A is age and the Greek letters represent parameters to be estimated. Bailey and Clutter(1974) described a procedure to fit the Schumacher model to measurements of average dominant height (H_1 and H_2) taken from the same plots at two different ages (A_1 and A_2) and produce either anamorphic or polymorphic site index curves. Their approach is essentially an algebraic difference formulation. Borders et al.(1984) further studied this approach and some other techniques. Their analysis included the Bailey(1980) model. The algebraic difference approach amounts to solving for one parameter in the model as a function of A_1, H_1 and the other parameters, and then substituting that solution into the model to express H_2 as a function of A_2, A_1, H_1 and the remaining parameters. The choice of a parameter to eliminate by this approach determines the behavior of the model. Choosing a particular parameter implies a specific growth relationship (derivative of the size-age functional relationship) in the form of a differential equation. The final expression of the model is the solution to this differential equation with the initial condition that $H=H_1$ when $A=A_1$. Examples with forestry interpretations are given using several growth models.

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INTRODUCTION

Equations used to model the relationship between tree or stand size and age have received wide use in forestry. After Clutter's (1963) celebrated paper introduced the idea of compatibility between growth and yield models, the derivative-integral relationship between growth and yield has been accepted as an important property for such models. In this paper we show that such a relationship holds true for models produced by the algebraic difference equation (ADE) method (Borders and others 1984). We present some broad classes of growth models based on the ADE method, derive their respective yield equations and discuss their biological interpretations.

Throughout this paper "H" stands for height, "A" represents age, and "K" is reserved for the constant of integration or a transform of it. Greek symbols represent parameters. The term "individual" refers to either a tree or an even-aged stand; "class" designates a set of individuals with some common characteristic such as site index. Even though all equations are developed with H as the response variable, the results could be applied equally well to other size variables, i.e. diameter, volume, etc. Optimum estimation of parameter values is not considered. However, most of the models are nonlinear in the parameters and this topic would not be straightforward.

Certain ideas behind the ADE method were presented by Bailey and Clutter (1974) who proposed a method to construct base-age invariant polymorphic site index curves. Their method "... essentially consists of identifying a parameter in the equation responsible for curve shape and allowing this parameter to be site specific.... The final step is the solution for H as a function of A, A_b [base-age], and S [site index]." This method is included in the text by Clutter and others (1983) under the name "Difference Equation" method, it is proposed not only to generate site index curves, but also for the development of yield equations. An advantage of this method is that it recognizes the association between two measurements at different ages on the same individual. The quote from Bailey and Clutter (1974) is a more general and articulate phrasing of a basic idea proposed by Schumacher (1939).

This same procedure, called the "Algebraic Difference Equation" (ADE) method, was used by Borders and others (1984) along with a splining technique to produce polymorphic site index curves. Their data base included more than two measurements on the same plots, but they used them just as independent pairs, each one made up of consecutive measurements. That is, the set $\{A_i, A_{i+1}, H_i, H_{i+1}\}$ was considered an observation for the estimation procedures described therein, hence no relationship was maintained between $\{A_i, H_i,\}$ and $\{A_{i+j}, H_{i+j}\}$ for j>1.

The primary objective of this paper is to discuss the implied differential equations for growth rate when ADE's are derived from some well known yield models by treating different parameters as class specific. This is eqivalent to the idea of site specific in the case of site index models.

DISCUSSION

Consider the Schumacher (1939) model after replacing volume by height:

$$\ln(H) = \alpha + \beta A^{-1} \tag{1}$$

Following the ADE sequence, let α be specific to a given individual and β be a general parameter for the population. For any arbitrary height-age pair (H_1, A_1),

$$\alpha = \ln(H_1) - \beta A_1^{-1}$$

Since β is common to all individuals, for any two height-age pairs observed on the same individual, we can write

$$\ln(H_2) = \ln(H_1) - \beta (A_2^{-1} - A_1^{-1}) \tag{2}$$

In this way we can use the two available measurements to estimate the parameter β in equation (2), which can be transformed into a site index model by replacing (H_2, A_2) with (S, A_b). Note that α from (1) does not appear in (2).

In (1), $\alpha = \ln(H_\infty)$ is the logarithm of the maximum attainable size. If we assume that all the individuals share the same α, then β may be considered individual specific and we may write $\beta = [\ln(H_1) - \alpha] A_1$. With two height-age pairs, the ADE is

$$\ln(H_2) = \alpha + [\ln(H_1) - \alpha] A_1 A_2^{-1} \tag{3}$$

The application and interpretation of (3) was discussed by Bailey and Clutter (1974). This formulation can be used to derive site index curves if we let $(H_2, A_2) = (S, A_b)$.

It is clear that the individual-specific parameter will not appear in the final formulation of the ADE, regardless of which model has been used. This is so because the parameter is removed in order to satisfy the specificity assumption. This parameter, following the ADE sequence, corresponds to the constant of integration, K, of the solution of a certain differential equation. This differential equation can be used to identify some characteristics of the growth rate implied by the ADE.

Consider the following differential equations:

$$\frac{\partial H}{\partial A} = -H\beta A^{-2} \qquad (4)$$

has the solution

$$\ln(H) = \beta A^{-1} + K \qquad (5)$$

and

$$\frac{\partial P}{\partial A} = -A^{-1}P \ln(P) \qquad (6),$$

where $P = (H/H_\infty)$, has the solution

$$\ln(H) = \alpha + KA^{-1} \qquad (7)$$

Recall that K stands for the constant of integration or a transform of it, so that equations (5) and (7) prove our claim. If K in (5) or (7) is used to satisfy the initial condition (H_1,A_1), then equations (2) and (3) obtain.

RESULTS

Using the arguments of the previous Section it is possible to determine the underlying differential equation for any ADE construct. By doing so it is possible to show the assumptions implied concerning growth, i.e. viable biological interpretations if one wishes, which in many cases are a very believable set of hypotheses. To illustrate this point we present several cases below, most of which result in growth functions already proposed and used in the literature.

CASE 1. The following relationships are proposed:

(i) There exists a maximum attainable size (H_∞), specific to an individual or a subclass, but not common for the whole class.

(ii) The rate of growth in H, $(\partial H/\partial A)$, is proportional (β) to the current size (H), which is a function of age (A).

(iii) The rate of growth is inversely proportional to the proportion (P) of maximum size (H_∞) which has currently been attained ($H = PH_\infty$; $0 \le P \le 1$), where P is a function of age.

(iv) The rate of growth is proportional to the rate of change in P with respect to age.

Proposition (i) above appears widely in growth theory; few objections, if any, could be made against it. It is unique for an individual or a subclass so that it allows for the concept of "site specific" (individual specific) often used in forest modelling. Proposition (ii) is also a frequent argument in growth/decay constructs. The larger the tree, the more biomass it is able to accumulate. However, this assumption implies certain restrictions. The difference between anabolic and catabolic processes changes with size. It starts small and increases. Next it reduces its productivity up to some point and thereafter no more accumulation is possible. It may even start a decay process, but most models, including ours, do not consider such an effect. So the influence of (ii) should be diminishing for large ages. Proposition (iii) allows for this behavior and is therefore a suitable complement for (ii). Proposition (iii) hypothesizes an inverse influence of P on the growth rate, but it is clear that as P increases so does H and the proportional influence of the rate of growth of P on the rate of growth of H is obvious; hence item (iv). Thus, these four propositions seem to be a well structured set of relationships which translate mathematically into:

$$\frac{\partial H}{\partial A} = \beta\, H\, P^{-1}\left[\frac{\partial P}{\partial A}\right] \qquad (8)$$

If $P = H/H_\infty$ is substituted directly into (8), it leads to an uninteresting result with $\beta=1$ and a redundant equation, which shows that (8) is consistent. From the definition of terms and assumption (i), obviously P as a function of age must take on values zero to one as age takes on values zero to infinity. This allows us to introduce the following proposition:

(v) P is a non-decreasing function of A, such as certain cumulative probability distribution functions (cdf), taking values from zero to one as A goes from zero to infinity.

The purpose of using a probability function is just a matter of convenience, but this is not a new idea in growth theory developments. As examples we can recall the Gompertz and the Logistic models.

SUBCASE 1.1. Let $P(A) = e^{-(1/A)}$, a transform of the exponential probability distribution. Then (8) simplifies to:

$$\frac{\partial H}{\partial A} = \beta\, H\, A^{-2} \qquad (9)$$

Which was presented before as equation (4) (the negative sign is absorbed into β) and yields the Schumacher model. The relationship with the ADE was discussed above.

SUBCASE 1.2. Now let P(A) be the 2-parameter Weibull cdf (which has the exponential cdf and several other distributions as special cases):

$$P(A) = 1 - e^{-(A^{\gamma}/\lambda)} \qquad (10)$$

Then equation (8) becomes

$$\frac{\partial H}{\partial A} = \beta\, H\, [1-e^{-(A^{\gamma}/\lambda)}]^{-1}\, e^{-(A^{\gamma}/\lambda)}\, (\gamma/\lambda)\; A^{\gamma-1} \qquad (11)$$

The solution of this equation is:

$$\ln(H) = \beta\, \ln[1-e^{-(A^{\gamma}/\lambda)}] + K$$

$$H = K\, [1-e^{-(A^{\gamma}/\lambda)}]^{\beta} \qquad (12)$$

Note that K is used for the constant of integration or any transform of this constant. The ADE formulation based on (12) using K to satisfy the initial condition implies (11); hence, this ADE construct implies the growth assumptions behind (11) already discussed. Equation (12) was proposed as a yield function by Bailey (1980) and used by Borders and others (1984) in an ADE formulation. If $\gamma=1$ in (10), P(A) becomes the exponential cdf and (12) would be transformed into the Richards(1959) function.

CASE 2. This construct is also based on the differential equation given as (8), however, H_{∞} is now assumed common for all individuals in the class, hence modifying assumption (i). Also proposition (v) is somehow altered; let us propose P to be the Gompertz cdf (Ahuja and Nash 1967). The domain of the argument of this function is the whole real line so that we will use ln(A) as the argument. Note that under this transformation many other cdf's might be used. Now with

$$P(A) = e^{-e^{-\ln(A)}}$$

equation (8) is transformed to

$$\frac{\partial H}{\partial A} = -\beta\, H\, A^{-1}\, \ln(P) \qquad (13)$$

Upon solving (13) we find:

$$\ln(H) = \ln(H_{\infty}) - KA^{-\beta} \qquad (14)$$

This is the model used by Bailey and Clutter (1974) to develop base-age invariant polymorphic site index curves. As before, K is a transform of the constant of integration and corresponds to the parameter which will be specific to an individual. Some signs do not match because the ranges of the parameters have not been included in the discussion.

Equation (13) may be given an interesting interpretation. We can define "Current Increment" (CI) as the instantaneous rate of growth in H ($\partial H/\partial A$) and "Mean Increment" (MI) as H divided by A; note the close parallel between these two definitions and the concepts of current annual increment (CAI) and mean annual increment (MAI) so familiar to foresters. Now we can write (13) as:

$$CI = -\beta\, MI\, \ln(P)$$

If CI and MI are replaced by CAI and MAI, and P is treated as a discrete variable (also annual), then for year t we have:

$$CAI(t) = -\beta\, MAI(t)\, \ln[P(t)]$$

So that for year t+1 the size is:

$$H(t+1) = H(t) + CAI(t) \qquad (15)$$

This last equation is a function g of the form $x(t+1)=g(x(t))$, and is recognized as a true difference equation (Huseyin 1986 page 20). Usually it is more difficult to find closed form solutions for difference than for differential equations, but expression (15) could be developed into interesting constructs.

CASE 3. For the following results, sets of assumptions which basically involve appropriate changes in the scale of measurement could be formulated. For reasons of space, and because the justification is not as straightforward as before, each of the next subcases now starts with a plain differential equation followed by its solution.

SUBCASE 3.1.

$$\frac{\partial H}{\partial A} = \ln[\ln(P^{1/\beta})] \ln(P)\, H\, [\ln(A)]^{-1} A^{-1} \qquad (16)$$

After some algebraic manipulation, which includes appropriate signs to keep the logarithmic function defined, (16) can be solved to give:

$$\ln(H) = \ln(H_\infty) + \beta A^{-K} \qquad (17)$$

In this equation, K comes from the constant of integration for the solution of (16). Thus, (16) is the differential equation implied by an ADE based on (17) when making the parameter K site specific. Although not used to develop their site index model, equation (17) was presented by Bailey and Clutter (1974).

SUBCASE 3.2:

$$\frac{\partial H}{\partial A} = \frac{H_\infty P \ln(P)\, e^{-\beta A^{\gamma}} \beta\gamma A^{\gamma-1}}{(1-e^{-\beta A^{\gamma}}) \ln(1-e^{-\beta A^{\gamma}})} \qquad (18)$$

Developing a biological rationale for expression (18) is not easy, but it can be done after diligent effort and appropriate definitions for terms. It is possible that some flexibilities not present in other constructs might accrue with the use of equation (18). The solution is:

$$H = H_\infty (1 - e^{-\beta A^{\gamma}})^{K} \qquad (19)$$

As before, K is a transform of the constant of integration and is used to satisfy initial conditions on growth. This development is equivalent to an ADE formed by solving for the parameter K in (19) in order to satisfy the specificity hypothesis. Equation (19) was presented above as (12); they are different in that the initial conditions on growth are imposed through a different parameter.

FINAL REMARKS

The results of this paper show the consistency of the ADE constructs. At the same time, the procedures utilized offer the possibility of studying the implied growth functional forms in order to discuss some biological interpretations. We have constrained this paper to show some of the published models used in ADE's. However, the principles presented to reach our objective have a much wider applicability and can be used to develop sound elaborations on growth theory.

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ALTERATIVE METHODS FOR IMPROVING THE VARIANCE APPROXIMATION OF SINGLE TREE GROWTH AND YIELD PROJECTIONS

George Gertner[1]

ABSTRACT. Gertner (1987) used first-order approximations to obtain the variance estimates of projections made with a single tree growth and yield model. Although the method used was found to be computationally very efficient in comparison to traditional Monte Carlo techniques, the variance estimates for some projected attributes were found to be biased. In this paper, some alternative methods for improving the variance approximations are considered. They include reformulating the first-order variance approximations and the use of higher-order approximations.

INTRODUCTION

Gertner (1987) presented an error propagation method for approximating the variance of predictions made with a variation of the individual tree growth and yield model, STEMS (Stand and Tree Evaluation and Modeling System) (Belcher, et al., 1982). The error propagation method provides a direct method for calculating the variance in a computationally efficient manner. For each function in the growth model, a first-order approximation was used to approximate the variance of prediction made with the function when there is random error in the input of the function. By approximating the variance for each function, the random errors that pass from one function to another can be approximated and accounted for (Figure 1). With an iterative model such as a multi-year projection system, the initial errors entered into functions of the model might be due to sampling errors and measurement errors in the state variables. After the first iteration, the errors will be due to errors in predictions from past iterations. With each additional iteration, the variance will increase as errors propagate through the system. The final variance of the prediction from the overall system will be due to the accumulation of all the errors.

In a comparison made between the variance approximations obtained using the error propagation and the Monte Carlo methods, the variance of some attributes obtained with the error propagation method were found to be biased. The error propagation method approximation of the standard deviation (square of variance) diverged at its worse from the Monte Carlo approximation by 16% for a 50-year projection. The purpose of this paper is to present some ways being considered for improving the variance approximations when using the error propagation method.

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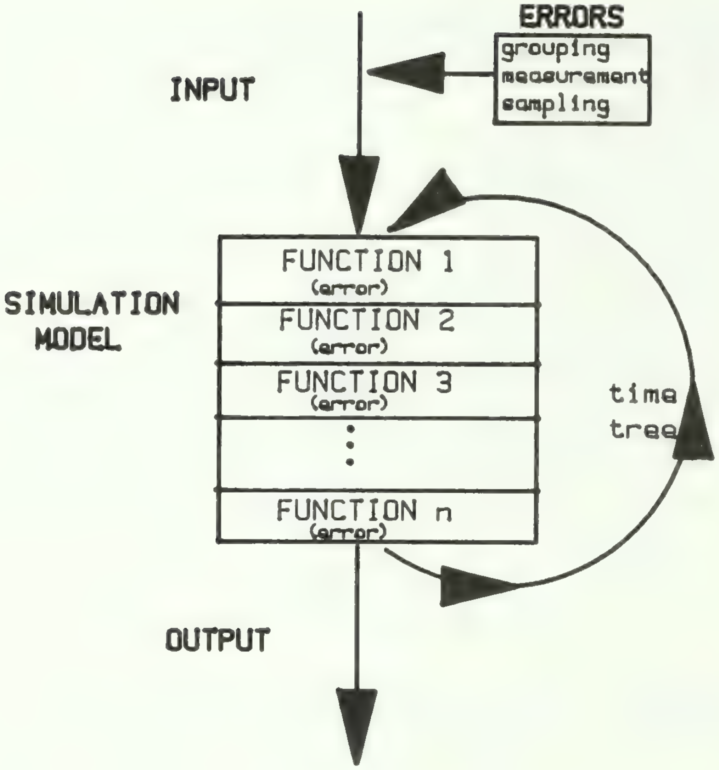

FIGURE 1. Errors propagating through component functions.

ERROR PROPAGATION METHOD

First-Order Approximation

The first-order approximation used by Gertner is presented very briefly. Suppose the following exact function is used to make predictions:

$$Y=f(B',X)$$

where Y is a prediction made with the function, $X=(X_1,X_2,X_3,...,X_q)$ are q input variables of the function, and $B'=(B_1,B_2,B_3,...,B_p)$ is a vector of known parameters. Usually X is assumed to be error-free. However, suppose that the attribute X_j is not measured exactly, but with error u_i, such the the observed attribute is $x_j=X_j+u_j$. Assume these errors are unbiased and independently distributed with a mean of 0 and variance of $vu(x_j)$. If the random errors are assumed to be independent between each of the independent variables, using a first-order Taylor series expansion, the prediction made with the function when X has error would be (Dahlquist and Bjork, 1974):

$$Y \approx f(\mathbf{B}',\mathbf{X})+\sum_{j}^{q}(\partial f/\partial X_j)\cdot(x_j-X_j)$$

Assuming higher-order terms are not significant, the expect value of the prediction is

$$E(Y) \approx f(\mathbf{B}',\mathbf{X})+\sum_{j}^{q}(\partial f/\partial X_j)\cdot E(x_j-X_j)$$

$$=f(\mathbf{B}',\mathbf{X})$$

and variance of the prediction based on the first-order approximation is

$$vu(Y)=E(Y-E(Y))^2 \approx E[\sum_{j}^{q}(\partial f/\partial X_j)\cdot E(x_j-X_j)]^2$$

$$=\sum_{j}^{q}[(\partial f/\partial X_j)^2\cdot vu(x_j)] \qquad \text{(Eq.1)}$$

where $(\partial f/\partial X_j)$ is the partial derivative of $f(\mathbf{B}',\mathbf{X})$ with respect to X_j.

This approximation is for a function that is exact and is not calibrated with a fitting procedure, for example, ordinary least squares, general least squares, or a maximum likelihood estimator. When the function is not exact, observations $Y_1,Y_2,Y_3,...,Y_n$ are postulated as having arisen from the function such that

$$Y_i=f(\mathbf{B}',X_i)+e_i \qquad i=1 \text{ to } n$$

where Y_i is the observed dependent variable; n is the number of observations; $\mathbf{B}'=(B_1,B_2,...,B_p)$ is a vector of unknown parameters that are estimated with a fitting procedure; $X_i=(X_{i1},X_{i2},X_{i3},...,X_{iq})$ is the ith error-free observation of q independent variables; e_i is process error or measurement error of Y_i (the difference between the observed and predicted dependent variable).

As it stands, if the error propagation approximation (Eq.1) is used for a calibrated function, the approximated variance of the prediction will be too low because the variance about the function, v(e), is not taken into account. The approximation (Eq.1) can be modified to include v(e):

$$vu(Y) \approx \sum_{j}^{q}[(\partial f/\partial X_j)^2\cdot vu(x_j)]+v(e) \qquad \text{(Eq.2)}$$

Function Reformulation

Originally Eqs. 1 and 2 were applied directly to the calibrated and exact functions of a variation of the STEMS model without considering the form of the functions. Through a systematic analysis to locate the source(s) of bias in the variance approximation, it was found that the variance approximation for both calibrated and exact functions that were used to predict cumulative individual tree attributes expanded to a per unit area basis were biased in comparison to the Monte Carlo approximations.

By recasting these cumulative tree functions to be recursive functions, it was possible to reduce the bias in the variance when Eqs.1 and 2 were applied to these reformulated functions. The statistical explanation for this will be presented in a later paper.

An example where this was done is in the calculation of basal area of a tree expanded to per acre basis. Originally, basal area of a tree expanded to per acre basis was calculated with the formula

$$BAE(i,t+1)=C\cdot DBH(i,t+1)^2\cdot TEF(i,t+1)$$

where DBH(i,t+1) is the diameter at breast height of tree i at time t+1, TEF(i,t+1) is the tree's expansion factor (the number of trees per acre represented by the projected tree) and C is a constant, C=.005454. Then basal area of the stand was obtained by summing across trees:

$$BA(t+1)=\sum_i BAE(i,t+1)$$

The variance of BAE and stand BA at time t+1 were then approximated with the formulas

$$vu(BAE(i,t+1))\approx C^2\cdot[DBH(i,t+1)^4\cdot vu(TEF(i,t+1)) +(2\cdot DBH(i,t+1)\cdot TEF(i,t+1))^2\cdot vu(DBH(i,t+1))]$$

and

$$vu(BA(t+1))=\sum_i vu[BAE(i,t+1)]$$

In reformulating the basal area function to be a recursive function, initial basal area of a tree expanded to a per acre basis prior to projecting was calculated as in the original function:

$$BAE(i,0)=TEF(i,0)\cdot BAT(i,0)$$

where $BAT(i,t)=C\cdot DBH(i,t)^2$. Then, after projecting the tree attributes, the function used for BAE was

$$BAE(i,t+1)=PS(i,t+1)\cdot BAE(i,t)+TEF(i,t+1)\cdot \Delta BAT(i,t+1)$$

where ΔBAT(i,t+1) is the change in basal area of a tree from time t to t+1 which is equal to $\Delta BAT(i,t+1)= (2\cdot AD(i,t+1)\cdot DBH(i,t)^2+AD(i,t+1)^2))$. Here PS(i,t+1) is the predicted annual probability of survival and AD(i,t+1) is predicted annual diameter growth. With this equation, BAE is recursively updated through time. The stand basal area at t+1 can then be calculated as before by summing across trees:

$$BA(t+1)=\sum_{i} BAE(i,t+1)$$

The recursive function for BAE can be shown to give the same predictions of basal area as with the original function, but the approximation of the variance will be different. The variance approximations for BAE and stand BA are:

$$\begin{aligned} vu(BAE(i,t+1)) \approx [&BAE(i,t)^2 \cdot vu(PS(i,t+1)) \\ &+PS(i,t+1)^2 \cdot vu(BAE(i,t)) \\ &+(C \cdot TEF(i,t+1) \cdot (2 \cdot DBH(i,t)+2 \cdot AD(i,t+1))^2) \cdot vu(AD(i,t+1)) \\ &+(C \cdot TEF(i,t+1) \cdot (2 \cdot AD(i,i+1))^2) \cdot vu(DBH(i,t)) \\ &+(C \cdot (2 \cdot AD(i,t+1) \cdot DBH(i,t)+AD(i,t+1)^2)^2) \cdot vu(TEF(i,t+1))] \end{aligned}$$

and

$$vu(BA(t+1))=\sum_{i} vu[BAE(i,t+1)]$$

Similarly, the same was done with the calibrated functions. For example, the cubic foot volume of a tree was predicted as a function of DBH(i,t), and site index (SI):

$$VT(i,t)=f(DBH(i,t),SI)$$

The initial total cubic foot volume of a tree expanded to a per acre basis prior to growth projection

$$VTE(i,0)=f(DBH(i,0),SI) \cdot TEF(i,0)$$

and the total cubic foot volume of a tree after projection would be updated with the function:

$$VTE(i,t+1)= PS(i,t+1) \cdot VTE(i,t)+TEF(i,t+1) \cdot \Delta VT(i,t+1)$$

where

$$\Delta VT(i,t+1)=f((DBH(i,t)+AD(i,t+1)),SI)-f(DBH(i,t),SI)$$

is the change in volume from time t to t+1. The volume per unit area would then be:

$$VS(t+1)=\sum_{i} VTE(i,t+1)$$

Eq. 2 would then be applied to these revised equations. Since differencing was used for calculating the change in volume, DVT, the variance about the function used in Eq. 2 had to also be revised to account for the differencing.

Comparison

The predictions and variance approximations using the revised functions were compared to those obtained with the original functions and with the Monte Carlo method. Details about the forest plot used for the comparison, model estimation, error specification, etc., can be found in Gertner.

The projections made with the revised functions were found to be exactly the same as with the original functions, and were nearly identical to those obtained with Monte Carlo method. Figure 2 shows the relative differences in the standard deviations obtained using the two formulations of the error propagation method versus those obtained with Monte Carlo method at year 50. The variance approximations using the revised functions were much improved. There was only a slight increase in computational time when using the revised functions (Table 1).

Second-Order Approximation

In addition to reformulating the functions in the model, the use of a higher-order approximations for calculating the variance for each of the functions was considered. When the first-order approximation was used, it was assumed that higher-order terms in the Taylor series were not significant. This assumption is acceptable when a function is fairly linear in form, but when a function is not, the variance approximation might prove to be poor.

Using a second-order approximation, the prediction made with a function when **X** is in error would be (Gelb et al.,1982):

$$Y \approx f(\mathbf{B}',\mathbf{X})+\sum_{j}^{q}(\partial f/\partial X_j)\cdot(x_j-X_j)+(1/2)\sum_{j}^{q}(\partial f^2/\partial X^2_j)\cdot(x_j-X_j)^2$$

Assuming the random errors are independent between each of the independent variables, the variance approximation based on the second-order expansion would then be

$$vu(Y)=E(Y-E(Y))^2 \approx E\Big[\sum_{j}^{q}(\partial f/\partial X_j)\cdot(x_j-X_j)+(1/2)\sum_{j}^{q}(\partial f^2/\partial X^2_j)\cdot(x_j-X_j)^2\Big]^2$$

$$= \sum_{j}^{q}[(\partial f/\partial X_j)^2\cdot vu(x_j)] + \sum_{j}^{q}[(\partial f^2/\partial X^2_j)(\partial f/\partial X_j)\cdot E(x_j-X_j)^3]$$

$$+ (1/4)\sum_{j}^{q}[(\partial f^2/\partial X^2_j)^2\cdot E(x_j-X_j)^4] \qquad \text{(Eq.3)}$$

where $E(x_j-X_j)^3$ and $E(x_j-X_j)^4$ are respectively the third and fourth moments of X_j. These are equivalent to the third and fourth moments of u_j. This expansion is for exact functions. For a calibrated function, the variance of about the regression has to be accounted for as done with the first-order approximation.

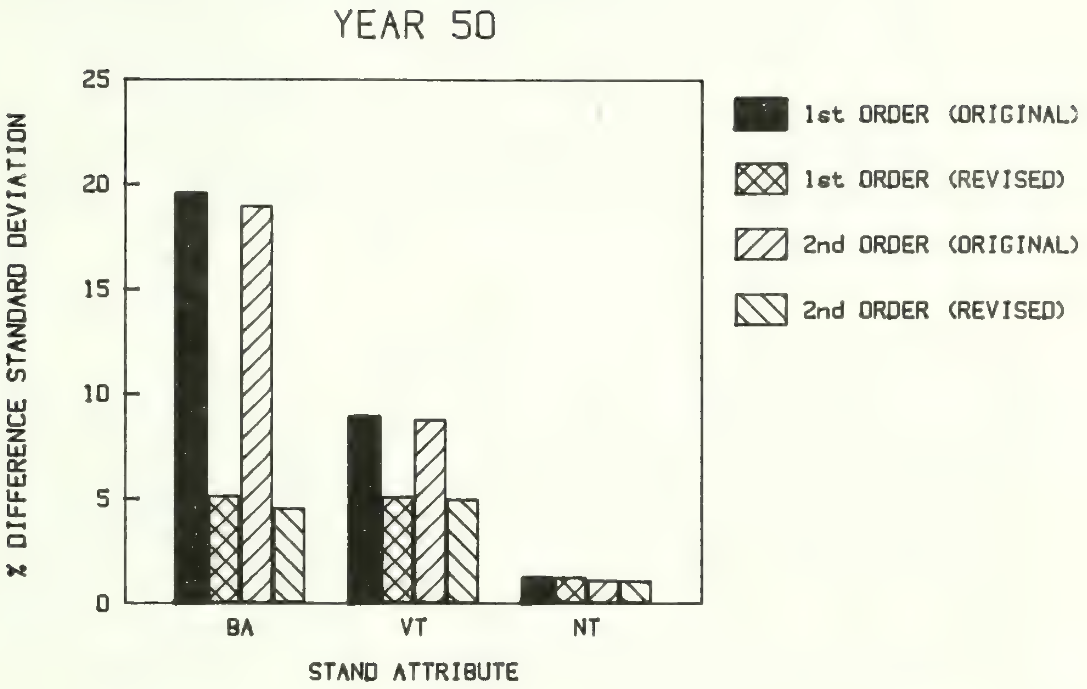

FIGURE 2. Percent difference in standard deviation approximations (BA=stand basal area, NT=number of trees, and VS=stand volume).

TABLE 1. Execution times[2] (CPU) to project stand 50 years.

METHOD	TIME (Seconds)	
Monte Carlo	16,673.97	(4.63 Hours)
Error Propagation		
First-Order (original)	8.67	
First-Order (revised)	9.89	
Second-Order (original)	11.32	
Second-Order (revised)	30.84	

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[2] The computer used was the University of Illinois' CDC Cyber 175 mainframe.

Comparison

The second-order approximation was applied to both the original and reformulated functions. When using the second-order approximation, both third and forth moments had to be calculated and stored. Shown in Figure 2 are the relative differences in standard deviations obtained using the second-order approximation versus the Monte Carlo method. Surprisingly, there was not much of an improvement in the standard deviation approximations for either the original or revised formulas. However, because the third and fourth moments had to calculated and stored, there was a significant loss in computational efficiency (Table 1).

CONCLUSION

Work is continuing on improving the approximations obtained using the error propagation method. For both the first-order and second-order approximations it was assumed that cross-product terms to account for possible correlation between the random errors of the independent variables of the functions were insignificant. Originally it was argued that the inclusion of the cross-product terms would likely have an insignificant effect on the final variance approximation, since the random errors of each of the variables of function will likely be an inextricable mixture of errors from past iterations. Currently, this assumption is being tested for it validity. If the assumption is found to be invalidate, the cross-product terms will be included. This, however, will make the implementation of the error-propagation very difficult.

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EVALUATION OF EXPLICIT AND IMPLICIT YIELD PREDICTION IN LOBLOLLY AND SLASH PINE PLANTATIONS IN EAST TEXAS

J. David Lenhart[1]

ABSTRACT. Explicit yield prediction models were more accurate than implicit yield prediction models in estimating unit-area cubic foot volume for loblolly (*Pinus taeda* L.) and slash (*Pinus elliottii* Engelm.) pine plantations in East Texas. Explicit and implicit models developed for loblolly pine plantations were more accurate than the models computed for slash pine plantations.

INTRODUCTION

Yield prediction systems can be divided into two basic categories--explicit and implicit (Clutter et al. 1983). Explicit methods provide for the direct estimation of the total amount of timber on an area, while implicit methods indirectly estimate the total amount of timber by summing across diameter classes. Explicit models are sometimes referred to as whole-stand or stand-level models. Diameter distribution yield prediction models are examples of implicit yield prediction.

Information from the East Texas Pine Plantation Research Project (ETPPRP), a long-term comprehensive study, provided an opportunity to evaluate the ability of the two yield prediction methods to estimate the total amount of timber per acre for loblolly and slash pine plantations on non-old fields in East Texas (Lenhart et al. 1985).

STUDY AREA

About three million acres of pine plantations have been established in East Texas on lands converted from natural timber stands. Of this acreage, approximately 85% has been planted with loblolly pine and the remainder with slash pine.

Throughout these pine plantations, the ETPPRP has established an array of permanent research plots. Each plot consists of two subplots--one for model development and the other for model evaluation. At this time, there are 173 plots in loblolly plantations, and 79 in slash pine plantations. Beginning in 1982 and on a 3-year remeasurement cycle, information has been collected on the development of the planted pines, in addition to other plantation parameters. Results reported in this study were derived from the first five years of measurements.

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Average values of plantation parameters are presented in Table 1. The plantations are young (about 10 years) with site index values that predict height growth to average about 3 feet per year. On the average, each loblolly pine tree has about 67 ft^2 of growing space, and each slash pine has about 100 ft^2.

TABLE 1. Summary of average stand values.

		Subplot	
Species	Item	Development	Evaluation
Loblolly	Age (yr.)	9.6	9.6
(n=183)	Stand Height (ft.)	31	31
	Site $Index_{25}$ (ft.)	74	74
	Surv. trees per Acre	458	467
	Cu. Ft. Wood per Acre	642	655
Slash	Age (yr.)	9.8	9.8
(n=87)	Stand Height (ft.)	29	29
	Site $Index_{25}$ (ft.)	70	70
	Surv. Trees per Acre	371	389
	Cu. Ft. Wood per Acre	438	425

EXPLICIT YIELD PREDICTION EQUATIONS

Modelling concepts that were first suggested by MacKinney et al. (1937), Schumacher (1939) and MacKinney and Chaiken (1939) were considered in the development of explicit yield prediction equations. Information from the model development subplots were analyzed and resulted in the following equations:

LOBLOLLY

$$CFW = EXP\ (9.2172 - 107.3059/H + 0.0009*T) \qquad R^2 = 96\% \qquad (1)$$

where CFW is the cubic feet of wood per acre in the total stem, H is the average total height (ft) of the ten tallest trees in the stand and T is the surviving number of trees per acre.

SLASH

$$CFW = EXP\ (8.5729 - 98.9909/H + 0.0015*T) \qquad R^2 = 96\% \qquad (2)$$

IMPLICIT YIELD PREDICTION EQUATIONS

A diameter distribution yield prediction method developed and presented by Burk and Burkhart (1984) for the Wiebull distribution was used in this study. Their method requires the estimation of minimum diameter (DMIN), quadratic mean diameter (DQMEAN) and mean diameter (DMEAN). Data from the model development subplots were utilized to compute the following prediction equations:

LOBLOLLY

$\text{DMIN} = -0.0353 + 0.0594*H - 0.0014*T \qquad R^2 = 72\% \qquad (3)$

$\text{DQMEAN} = \text{EXP}\ (2.7530 - 30.3366/H + 0.0005*T) \qquad R^2 = 96\% \qquad (4)$

$\text{DMEAN} = -0.1226 + 0.9920*\text{DQMEAN} \qquad r^2 = 99\% \qquad (5)$

SLASH

$\text{DMIN} = -0.2440 + 0.0698*H - 0.0014*T \qquad R^2 = 70\% \qquad (6)$

$\text{DQMEAN} = \text{EXP}\ (2.4908 - 26.4690/H + 0.0003*T) \qquad R^2 = 95\% \qquad (7)$

$\text{DMEAN} = -0.1044 + 0.9915*\text{DQMEAN} \qquad r^2 = 99\% \qquad (8)$

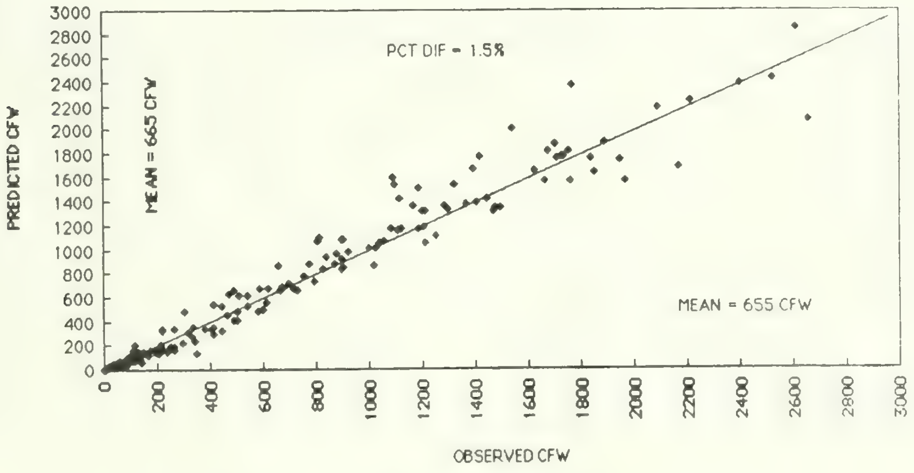
where predicted diameter is in inches.

After the parameters of the Weibull distribution are recovered, the expected number of trees per acre in each expected diameter class is determined. The appropriate content of an individual tree in each class is estimated and that value is multiplied by the number of trees per acre in the class. An unit-area value is obtained by summing across all diameter classes.

EVALUATION

LOBLOLLY

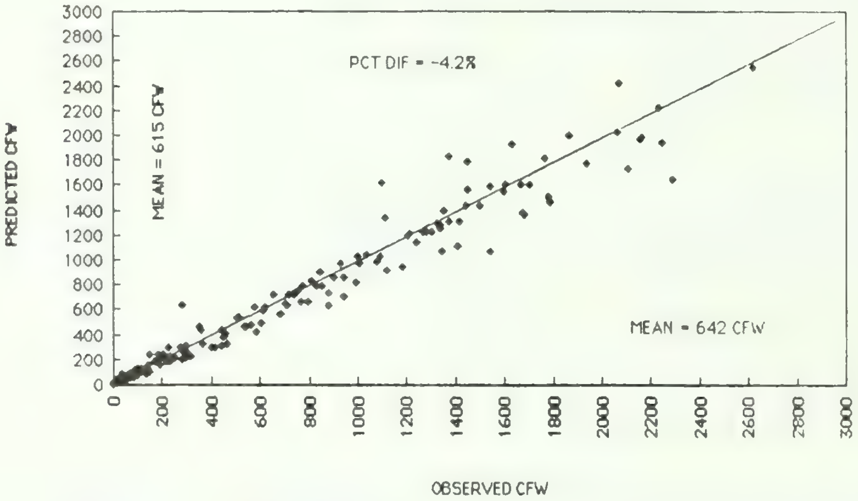
Using equation (1), an explicit CFW value was estimated for each of the 183 loblolly model evaluation subplots. The predicted CFW values were plotted over observed CFW values (Figure 1). A percent difference of predicted minus observed relative to observed was computed. For these evaluation subplots, there is an over-prediction of 1.5 percent. No bias is apparent.



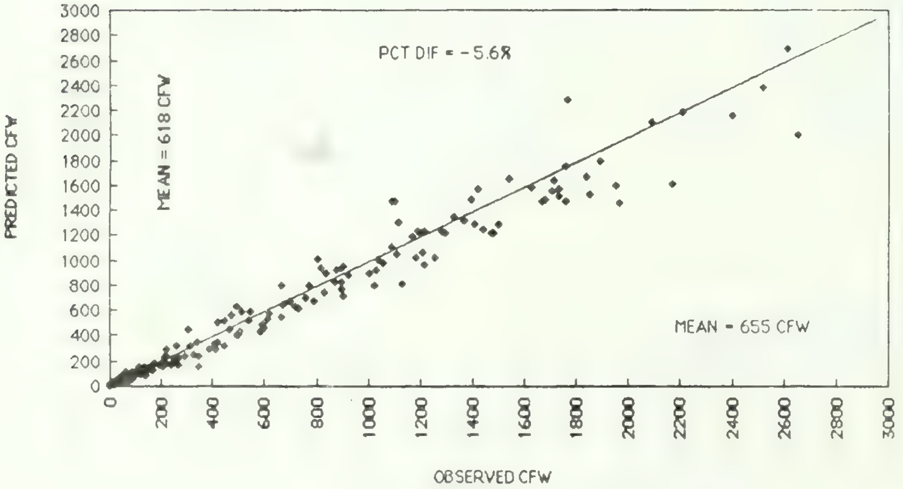
LOBLOLLY - EXPLICIT PREDICTION - MODEL EVALUATION SUBPLOTS

FIGURE 1. Predicted CFW plotted over observed CFW for explicit yield prediction.

Using equations (3), (4) and (5) in conjunction with the Burk and Burkhart (1984) method, an implicit CFW value was determined for each of the model development and model evaluation subplots. Plottings of the predicted CFW values over the observed CFW values are shown in Figure 2. For the development subplots, the mean percent difference is -4.2%, while for the evaluation subplots, the mean percent difference is -5.6%. No bias is apparent for the development subplots, however for the evaluation subplots, implicit yield prediction appears to underpredict the larger volume subplots.



LOBLOLLY - IMPLICIT PREDICTION - MODEL DEVELOPMENT SUBPLOTS



LOBLOLLY - IMPLICIT PREDICTION - MODEL EVALUATION SUBPLOTS

FIGURE 2. Predicted CFW plotted over observed CFW implicit yield prediction.

SLASH

Using equation (2), an explicit CFW value was predicted for each of the 87 slash pine model evaluation subplots. Figure 3 compares predicted CFW values to observed CFW values. Mean percent differing is 3.3%, and points seem to be well-distributed in an unbiased pattern.

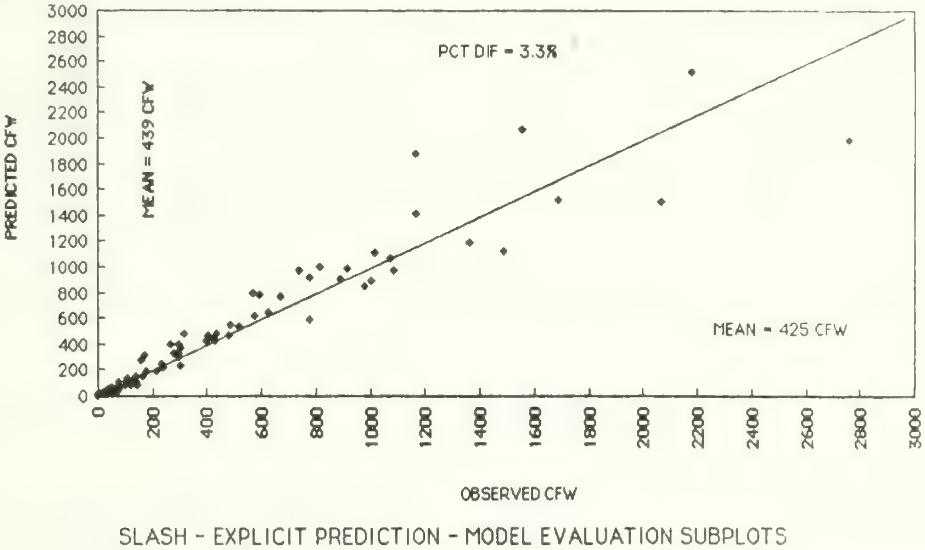
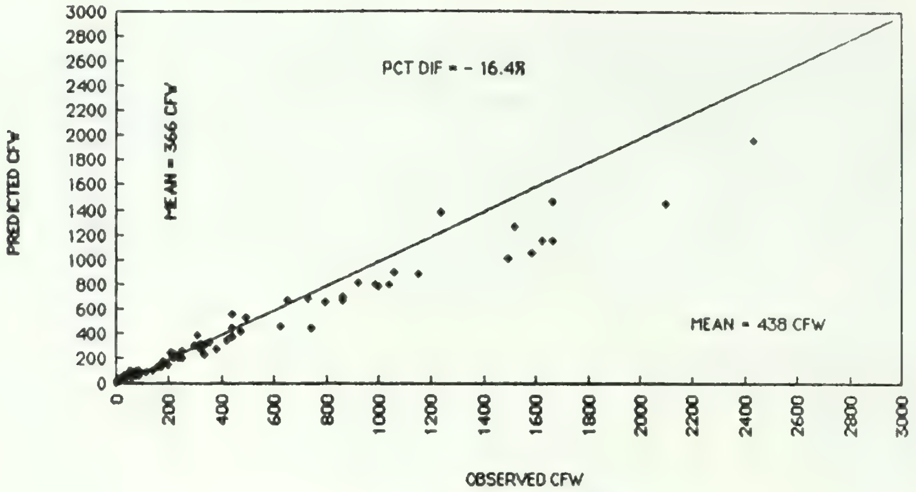


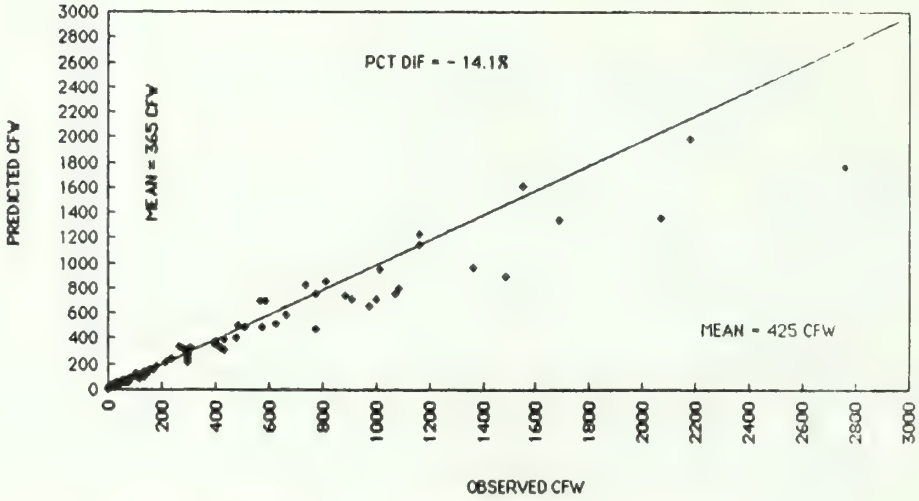
FIGURE 3. Predicted CFW plotted over observed CFW for explicit yield prediction.

Calculation of implicit CFW values were initiated with equations (6), (7) and (8). Plotting of predicted implicit CFW values over observed CFW values for the 87 model development subplots is shown in Figure 4. The mean percent difference is -16.4%. Evidently the implicit method did an unsatisfactory job of estimating the higher volume subplots. Figure 4 also illustrates the plotting of predicted implicit CFW values over observed CFW values for the model evaluation subplots. In this case, the mean percent difference is -14.1%. Implicit yield prediction for this sample set has difficulty in estimating the larger volume subplots.

Slash pine is an exotic in East Texas, which may account for the negative bias apparent in the implicit yield prediction method. Growth habit and characteristics of the East Texas slash pines may be affected by growing conditions outside of their native range. In addition, fusiform rust (Cronartium guercuum (Berk.) Miyabe ex Shirai f. sp. fusiforme) infects East Texas slash pine plantations at an average incidence rates of 50-60% (Hunt and Lenhart 1986). Implicit yield prediction methods developed in this study may be unable to reflect the influence of these environmental factors.



SLASH - IMPLICIT PREDICTION - MODEL DEVELOPMENT SUBPLOTS



SLASH - IMPLICIT PREDICTION - MODEL EVALUATION SUBPLOTS

FIGURE 4. Predicted CFW plotted over observed CFW for implicit yield prediction.

SUMMARY

An evaluation of explicit and implicit yield prediction systems applied to loblolly and slash pine plantations on non-old-fields in East Texas indicates that results vary between methods and between species. When explicit methods were applied, relatively small differences in predicted minus observed unit-area volumes were noted for both species with loblolly the better. However, applying implicit methods resulted in larger differences in volumes. Once again, predictions for loblolly were better than slash, with slash being 3-4 times worse than loblolly.

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EVALUATION OF SELECTED MICRO-COMPUTER FOREST INVENTORY AND GROWTH MODELS FOR USE AT THE MANAGEMENT LEVEL IN THE SOUTHEASTERN US

Donald J. Lipscomb and Thomas M. Williams [1]

ABSTRACT. Three micro-computer software packages (TVA Inventory Processor, Tennessee Valley Authority, Norris, Tenn. ; Total Tree Multiproduct Cruise Program, Southeastern Forest Experiment Station, Asheville, N.C. ; CRUISE and STP, Resources Consulting Int., Starkeville,Miss.) were used to project the stand data for periods up to ten years. Accurately measured data from fixed area CFI plots in natural longleaf and loblolly pine stands are used to produce stand and stock tables using each inventory processor for 1976,1979,1984, and 1986. Growth projections of each program were made with the same growth data collected from each plot. TVA and CRUISE produced stand tables identical to hand calculation with Mesavage - Gerard tables.TTMP produced consistently higher volumes. Growth projections were adequate for whole forest projections for up to ten years. Individual stand data and projections expressed as annual growth rate were highly variable.

INTRODUCTION

Computational ability of micro-computers now rivals that of mainframe computers of the 1960's and early 1970's. Moderate sized land owners and small forestry consulting companies can now afford to have office computers capable of maintaining stand records for entire ownerships. The huge business software market developed around micro-computers has indoctrinated users to expect sophisticated user packages which often hide the basic operation of the program. Forestry software will often be judged by the same standards of "user friendliness" as is this business software.

One of the basic advantages of micro-computers is individuality. Individuals use the program of their choice, on data of their choice, to obtain the results of their choice. In deciding what programs will best meet an identified need the user might ask the following questions: 1).Do different programs produce the same results on identical data? 2)Do program results differ consistently or randomly on different data? 3)Are results of any one program more accurate ? To test these questions we assembled currently available micro-computer programs capable of receiving cruise tallies, computing volume by diameter class tables, and projecting future stand volume for southern pines. They were; TVA Inventory Processor (Bean and Ellis, 1984) CRUISE and STP (Parker 1982a, 1982b) and Total Tree Multiproduct Cruise Program (Clark et. al. 1985). These programs will be abbreviated TVA, CRUISE, STP, and TTMP respectively throughout the rest of this paper.

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Specifically our objectives were to answer the questions posed above from the perspective of the forest manager. Do these programs have the ability to meet the forest manager's needs in dealing with many tracts that vary in composition. While accuracy over an idealized data set is the main priority of the modeler the manager is more interested in utility. That is can a program produce predictions accurately and consistently enough to make sound silvicultural decisions for a forest.

The forest used in this study is located on Hobcaw Barony, a 17500 acre peninsula located between Winyah Bay and the Atlantic Ocean in eastern Georgetown County, South Carolina. The forest is composed primarily of longleaf pine (Pinus palustris Mill.) and loblolly pine (Pinus taedaL.) separated by lowland hardwoods on very poorly drained soils. The forest has a varied management history with several periods of logging, and stand ages varying from 0 to over 150 years (Williams and Lipscomb, 1985).

METHODS

DATA COLLECTION

Ten one fifth acre growth plots were chosen from a CFI experimental study. These plots were chosen to be pure pine natural stands. The plots were predominantly longleaf (five plots) and loblolly (five plots) pine. They represented a wide range of ages, sizes and basal areas (Table 1). All trees in each plot were measured for diameter and merchantable height and tagged in 1976. The same trees were then remeasured in 1979,1984, and 1986.

Table 1. Growth Plot Characteristics (1986)

Plot	Species	Age	Basal Area ft^2/ac	Volume Mbf/ac	Diameter Range	Ave. in.
19	Longleaf	153	61	12.7	4-21	12.0
40+	Longleaf	98	116	18.7	4-32	11.3
53	Longleaf	117	55	11.4	10-20	14.6
79	Longleaf	120	16	2.0	4-16	7.3
80	Longleaf	130	24	3.8	4-18	9.6
10*	Loblolly	75	52	7.9	4-28	-
17	Loblolly	38	112	14.3	6-17	10.7
29*	Loblolly	20	29	2.8	4-16	6.0
41	Loblolly	35	64	11.3	4-16	11.8
42	Loblolly	35	87	14.8	11-18	13.1

* Plots dropped from analysis due to age and faulty data collection

+ Plot dropped from 5 year analysis because tree was too large for TTMP program

In 1986 increment cores were taken from each plot. The number of trees cored in each plot was determined by the diameter distribution of the plot. At least two trees from each diameter class on the plot were cored. Only the dominant species of pine in the stand was cored. This procedure was selected as a reasonable representation of what would be practical in a larger scale periodic inventory. After coring a loblolly plot was found to be less than 20 years old. Since a ten year core prior to 1976 was needed this plot was eliminated. A second loblolly plot was also eliminated when errors in season of measurement were found that could not be resolved.

INVENTORY PROCESSING

The field tallies were made into input files for the three inventory processors and checked to be certain all processors analyzed the exact same data set. Several problems were found in the field data. On several plots a tree was missed in the 1976 measurement. On one longleaf plot a tree grew out of the diameter range of the TTMP program by 1979. The growth projection programs also presented limitations in the comparisons. TVA would only produce a ten year growth projection while TTMP would not project beyond five years. To maximize the data used in each program the data were analyzed as two separate data sets. Ten year projection could be done on eight plots with the 1976 and 1986 data. The 1986 data were modified so that the trees missed in 1976 were absent from both. Five year growth projections were done on seven plots with 1979 and 1984 data. All trees were measured in 1979.

TEN YEAR PROJECTIONS

The data were analyzed as two separate sets. Stand tables were calculated by CRUISE and TVA for the 1976 data on all eight plots. These tables were projected to give 1986 volumes. CRUISE stand tables were projected with the STP program. This program has three options as base assumptions: STP 1) a constant rate of diameter growth, STP 2) a constant rate of basal area growth, and STP 3) average of the two . All options were used in each analysis and are labelled on each figure. The TVA program produces a single ten year projected stand table. An actual stand table was created from the 1986 data by each program.

FIVE YEAR PROJECTIONS

The 1979 field data from seven plots (four longleaf and three loblolly) were processed by all three inventory processors. Growth data were entered from the cores for the period five years prior to 1979. Projected 1984 stand tables were created by TTMP and STP. Three separate stand tables were created with STP using the same growth assumptions as in the ten year comparison. Two separate stand tables were created with TTMP, one using the local core data and one using regional averages provided in the program. These predicted stand tables were compared to 1984 stand tables created by the inventory processors using actual 1984 measurements.

RESULTS

The stands used in this study were all sawtimber size. Although other products were included in the reports we will present only the results for sawtimber. All models were run to produce sawtimber volumes in International 1/4" log rule with a form class of 78.

INVENTORY PROCESSORS

The inventory processors calculated different volumes from the same timber tallies (Figure 1.). CRUISE is the only program that visibly uses the Mesavage-Gerard tables for volume calculations. The program does not have a mechanism for cull, therefore, merchantable heights must be adjusted for cull during the cruising. In TVA there is a mechanism for cull to be entered on each measured tree. To keep the data exactly comparable we entered all trees as completely sound. In this case the TVA program calculates the exact same stand table volumes as the CRUISE program. For timber without cull both programs give the same volume that would be calculated by hand using the Mesavage - Gerard tables. The TTMP program uses a regression to approximate the Mesavage - Gerard tables and consistently gave a larger volume than the other processors.

TEN YEAR PROJECTIONS

The ten year projections were made with TVA and STP programs (Figure 2.). Since inventory processor results were identical both programs used the same stand tables from 1976. Growth data were obtained from cores for the ten years preceding 1976. When all eight plots are combined, the projections were within 5% of the measured 1986 volumes. Differences between the separate growth assumptions in the STP program were as large as between the STP and the TVA programs.

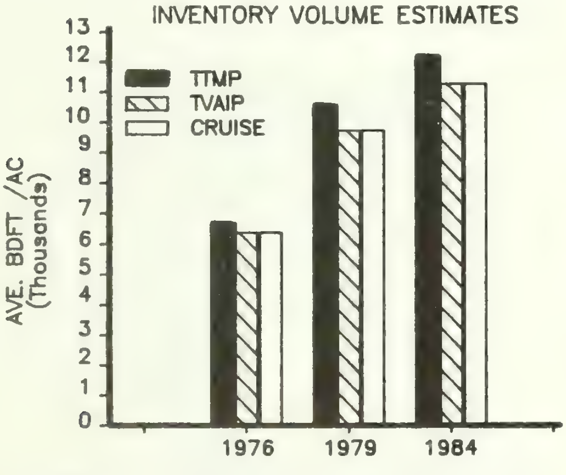

FIGURE 1. Comparison of inventory processors

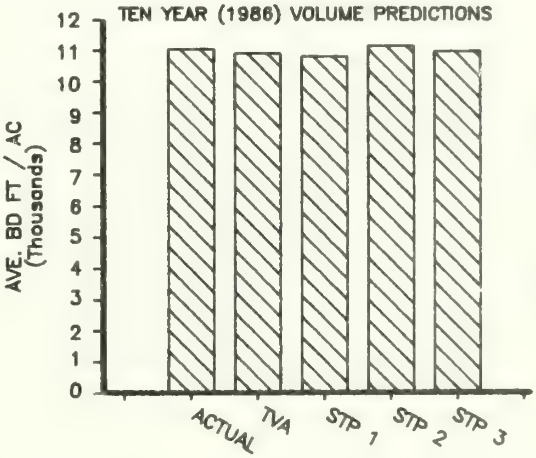

FIGURE 2. Comparison of ten year projections for five longleaf and three loblolly plots combined.

Individual plot results show more variability than the averages. Errors on individual longleaf plots ranged from a 13% underestimate to a 16% overestimate. On loblolly plots the largest overestimate and underestimate were 19%. There was no consistent trend in the errors. Some plots were underestimated on all models, some plots were over estimated on all models, and on some plots different models gave both under and over estimates (Figures 3 & 4).

The models also predict average annual growth increments (Figures 5 & 6). When rendered as an average annual growth rate the model differences are quite substantial. TVA had the largest underestimate in loblolly plots while it produced the largest overestimates for longleaf plots. On the loblolly plots errors of predicted annual growth were as high as 40% of the measured rate (Figure 7).

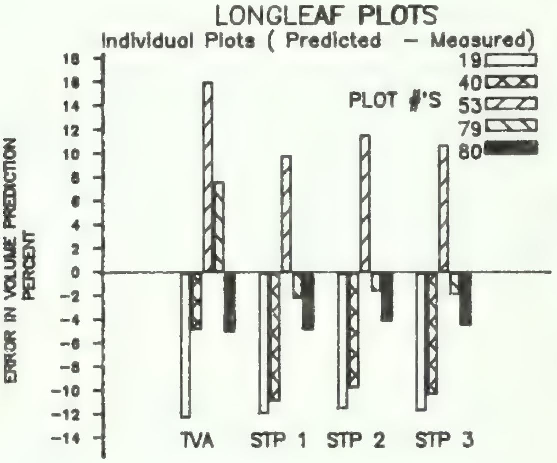

FIGURE 3. Comparisons of ten year volume predictions of individual longleaf plots.

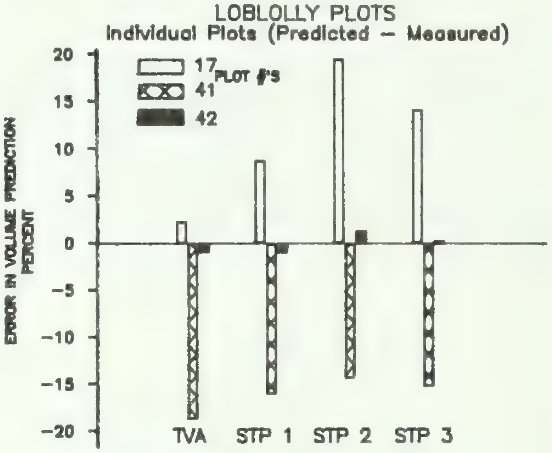

FIGURE 4. Comparison of ten year volume projections on individual loblolly plots

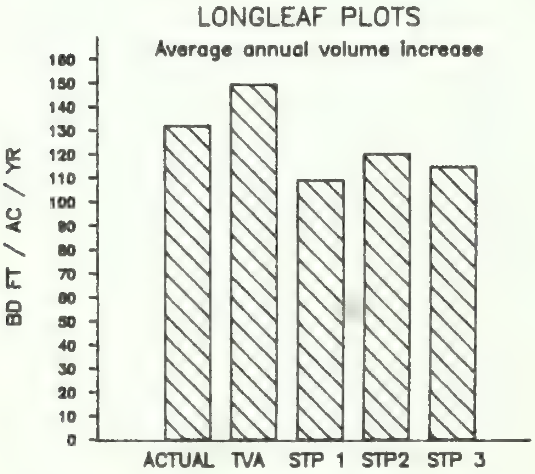

FIGURE 5. Comparison of average annual volume increment of ten year longleaf plots.

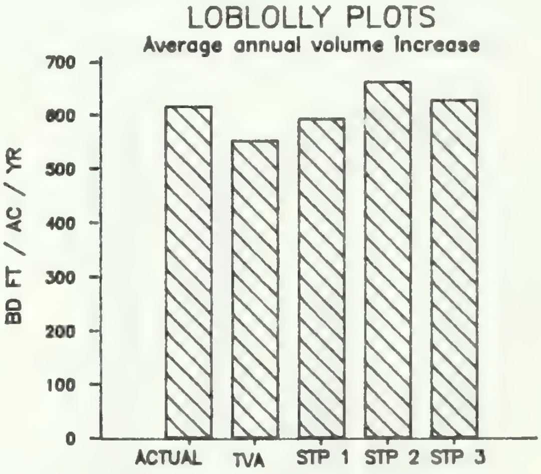

FIGURE 6. Comparison of average annual volume increment of ten year loblolly plots

FIVE YEAR PROJECTIONS

The five year projections were made with the TTMP and STP programs (Figure 8.) . The TTMP program inventory processor calculated a higher 1979 volume than the CRUISE program. Therefore, the TTMP growth projection program began with a slightly different stand table than the STP projections did. The resulting projections were all still within 5% of the 1984 volume computed by the CRUISE program.

Individual plot values varied in the five year data much as they did in the ten year set. Errors were slightly smaller with underestimates of only 9 % and overestimates as high as 13%. If cores were not taken the TTMP program uses estimates of regional average diameter growth rates to predict growth. When the program was run using this option the projections were generally poorer than those using local cores (Figure 9.).

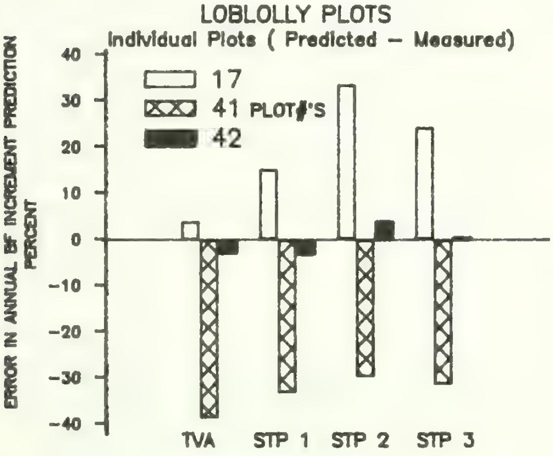

FIGURE 7. Comparison of individual predictions of average annual volume increases.

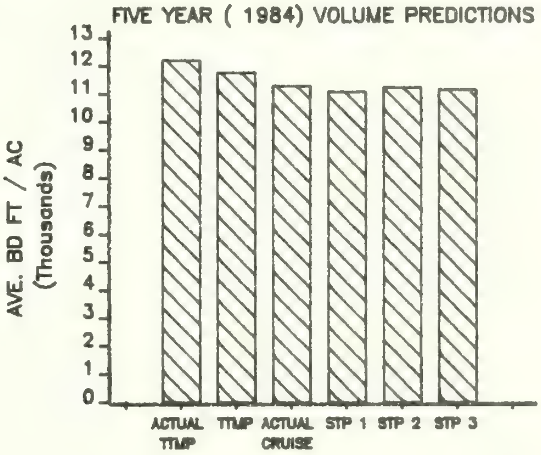

FIGURE 8. Comparison of five year projections of four loblolly and three longleaf plot combined

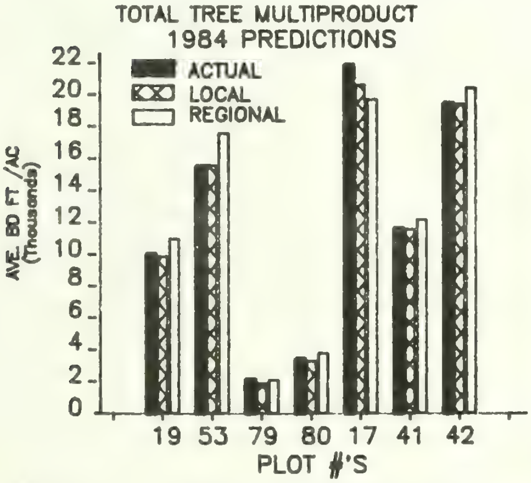

FIGURE 9. Comparison of Total Tree Multiproduct Cruise Program projections to individual plot measured volume with local core increments and regional averages provided in the program

CONCLUSIONS

All three of these programs are capable of calculating stand tables from cruise tally sheets. The CRUISE and TVA produce volume tables identical to hand calculation with standard volume tables. THe TTMP program produced slightly higher volumes than the other programs.

When several plots from pure pine stands of a wide range of diameters, ages, and density were combined volumes can be projected up to 10 years within 5% of actual measured values. However, on individual plots the volume predictions had considerably greater variability ranging from underestimates of 19% to overestimates of 19%. If differences are expressed as an annual volume growth rate the errors are as high as 40%. The programs differ considerably at the individual stand level given exactly the same initial conditions.

Working with these programs has also pointed out the multitude of decisions to be made about details. How are field height measurements to be made: total height, height to a 4" top, number of pulpwood sticks, or number of merchantable sawlogs. Only TTMP will take any of these measures of height. CRUISE and TVA will not use total height. How are trees with defect to be tallied? With CRUISE defect is deleted from the merchantable height but with TVA a percent soundness is entered into the program.

Micro-computers have brought about a new layer of people between the biometrician and the end user. Users previously chose an appropriate model from the literature. The user knew who the model builder was and had opportunity to directly discuss limits of the model's application. The micro- computer programer is now placed between the model builder and the end user. More often than not he will be attempting to make the operation of the model transparent to the user. Marketing of executable machine language files can completely sever the link from modeler to end user.

A new layer requires new commitments from each group. Biometricians should provide direct guidance for implementing their models into computer code. Clear statements of the range of applicability (geographic range, species, diameter or age range, stand type) of each model will be more critical than ever. Programmers will need to be responsible for coding model limits as well as operations. Positive deterrents to misuse of the model must be built into both the program and the documentation. Documentation needs to include all original citations to the models used to retain the link from user to modeler. Users must assure that the processing program they selects is not only accurate but suitable for their biological conditions and silvicultural applications. Rigorous validation procedures and comparisons of programs need to be developed by all three groups.

We see programs tested in this study as very useful to maintain current forest inventory information. Turner (1983) described such a system used by St. Regis . A portion (10-20%) of the forest ownership is measured each year. Inventory in all stands is determined annually by short term projections from the last measurement. With an accounting of cutting and planting such a system will produce a continuously up-to-date inventory. The plots evaluated in this study suggest that even on a cycle as long as ten years the overall error in inventory will not be more than 5%. For moderate to large land owners it seems such a procedure would be as effective and less costly than a CFI system combined with periodic inventories.

These programs did not produce results we believe would be useful in making economic decisions about application of forestry practices. Despite identical data from 100% cruises the various programs projected annual increments which ranged from 40% above to 40% below the actual measured growth. To prescribe economic return from silvicultural applications to individual stands, more precise increment projection will be needed.

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COMPARING REGRESSION CURVES

Ronald E. McRoberts[1]

ABSTRACT. The same form for a regression model is often used to estimate curves depicting the relationships between a response variable and its predictors for different conditions. Frequently it is desirable to test the hypothesis that there is no difference among the regression curves for these conditions or, equivalently, that there are no differences among the sets of model parameter estimates. An F-test is presented for comparing regression curves for two different conditions. Statistical power curves are presented for this test when the models are linear. When the models are nonlinear, this test may yield much less power than when the models are linear. Results based on simulations are shown for the allometric, negative exponential, Weibull, and Chapman-Richards models.

INTRODUCTION

An important application of regression analysis is the mathematical modelling of the relationship between response and predictor variables. Frequently the same model form, but possibly with different parameter estimates, is adequate for describing relationships between the same variables under different conditions. Recent issues of Forest Science include the following examples:

(1) the allometric model to describe the relationship between biomass and diameter for different stem densities (Clary and Tiedemann 1986),

(2) the negative exponential model to describe the relationship between height and the inverse of age for different planting densities (Pienaar and Shiver 1984a),

(3) the Weibull model to describe the relationship between cumulative percent shoot growth and elapsed time for different years (Perala 1985), and

(4) the Chapman-Richards model to describe the relationship between basal area per acre and age for different planting densities (Pienaar and Shiver 1984b).

After curves have been estimated for each of the different conditions, it may be desirable to determine if they are statistically significantly different. This paper describes a test for comparing regression curves for linear models and then evaluates its use for the four previously referenced nonlinear models.

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THE LINEAR MODEL TEST

The general linear regression model is denoted

$$Y_i = \beta_1 X_{1i} + \beta_2 X_{2i} + \dots + \beta_p X_{pi} + \varepsilon_i \quad (1)$$

for i=1,2,...,n, where Y is the dependent response variable; the X's are p independent, predictor variables; the β's are p unknown coefficients to be estimated; ε is a normally distributed residual error term with mean zero and variance σ^2; and n is the sample size.

The test of the hypothesis that two estimated linear regression curves are not different is similar to the one-way analysis of variance test of the hypothesis that two means are not different (Draper and Smith 1981, Ratkowsky 1983). Suppose that a data set of n observations of the dependent and independent variables is obtained under each of two different conditions. Furthermore, suppose that a linear model of the same degree is known to be adequate under each condition. For the null hypothesis,

> H_o: There are no differences between the curves representing the relationships between the variables under the two conditions,

the test requires three sums of squares error: SS_1 obtained from fitting the model to the first data set, SS_2 obtained from fitting the model to the second data set, and SS_c obtained from fitting the model to the two data sets combined. The test statistic is computed as

$$F = \frac{[SS_c-(SS_1+SS_2)]/p}{(SS_1+SS_2)/(2n-2p)} . \quad (2)$$

When the model is linear in the coefficients and the errors are independently, normally distributed with mean zero and constant variance, the F statistic defined in (2) follows the F distribution with p and 2n-2p degrees of freedom.

THE STATISTICAL POWER OF THE F TEST FOR LINEAR MODELS

The statistical power of a test is the probability that it will result in rejection of a hypothesis, H_o, when an alternative hypothesis, H_a, is valid. This is called the power of the test with respect to the alternative hypothesis, H_a. It is known that statistical power increases when residual variance decreases, when sample size increases, and when the difference between the hypotheses increases. A report in Science (1985) on scientific fraud characterized the reporting of experiments with low statistical power as the distortion of research results. Whenever a result of no significant differences is reported or forms the basis for further analysis, it is critical that there be a high probability of detecting significant differences if they exist.

Calculating the power for the F test of hypothesis of no difference between regression curves requires that the alternative hypothesis be quantified. Let d be the average minimum difference to be detected between the two curves if they are different. Let S be the sum over data sets and observations of this difference squared. Thus, $S=Nd^2$, where N is the sum of the sample sizes for the two data sets. Power curves for $\alpha=.05$, shown as functions of the ratio of S and σ^2, for one-, two-, and three-coefficient models are given in Figure 1. Note that although the curves estimate the probability of detecting S/σ^2, S may occur as the result of several quite different patterns of actual observations. Thus, it is appropriate to formulate the alternative in terms of an average minimum difference to be detected.

The curves were determined by simulating the comparison of linear models for combinations of residual variances, designs, and sets of coefficient values. Residual variances were selected to provide values of S/σ^2 in increments of 10. One thousand simulations were conducted for each combination of two designs, two sets of coefficient values, and values of S/σ^2. To obtain a smooth curve, a modified two parameter Weibull model,

$$Y = 1 - .95 \exp(\beta_1 X^{\beta_2}) + \varepsilon,$$

was fit to the data points. The Weibull model was selected because of its asymmetric distributional properties. The R^2 values were greater than .999 for this model, and there was no discernible or statistical lack of fit.

To demonstrate the use of these curves, consider a simple linear model with intercept and slope, two data sets with four points each, a preliminary estimate of σ as $s=.10$, and the null and alternative hypotheses formulated as follows.

H_o: No difference between the curves over the X values of interest

H_a: Average difference between curves over the X values of interest exceeds 0.4.

To reject H_o in favor of H_a, the average squared difference for the eight points should exceed 0.16. Thus, $S=8(.16)=1.28$ and $S/s^2=1.28/(.10)^2=128.0$. The power for $p=2$ coefficients, $N=8$, and $S/\sigma^2=128.0$ is approximately 0.90 (Figure 1).

TEST APPLIED TO NONLINEAR MODELS

When procedures based on linear model assumptions are applied to nonlinear models, the results are only approximate. The quality of the approximation depends on the curvature of the nonlinear model. Bates and Watts (1980) have shown that curvature depends on the particular model, the number of observations, the values of the independent variables, and the residual variance.

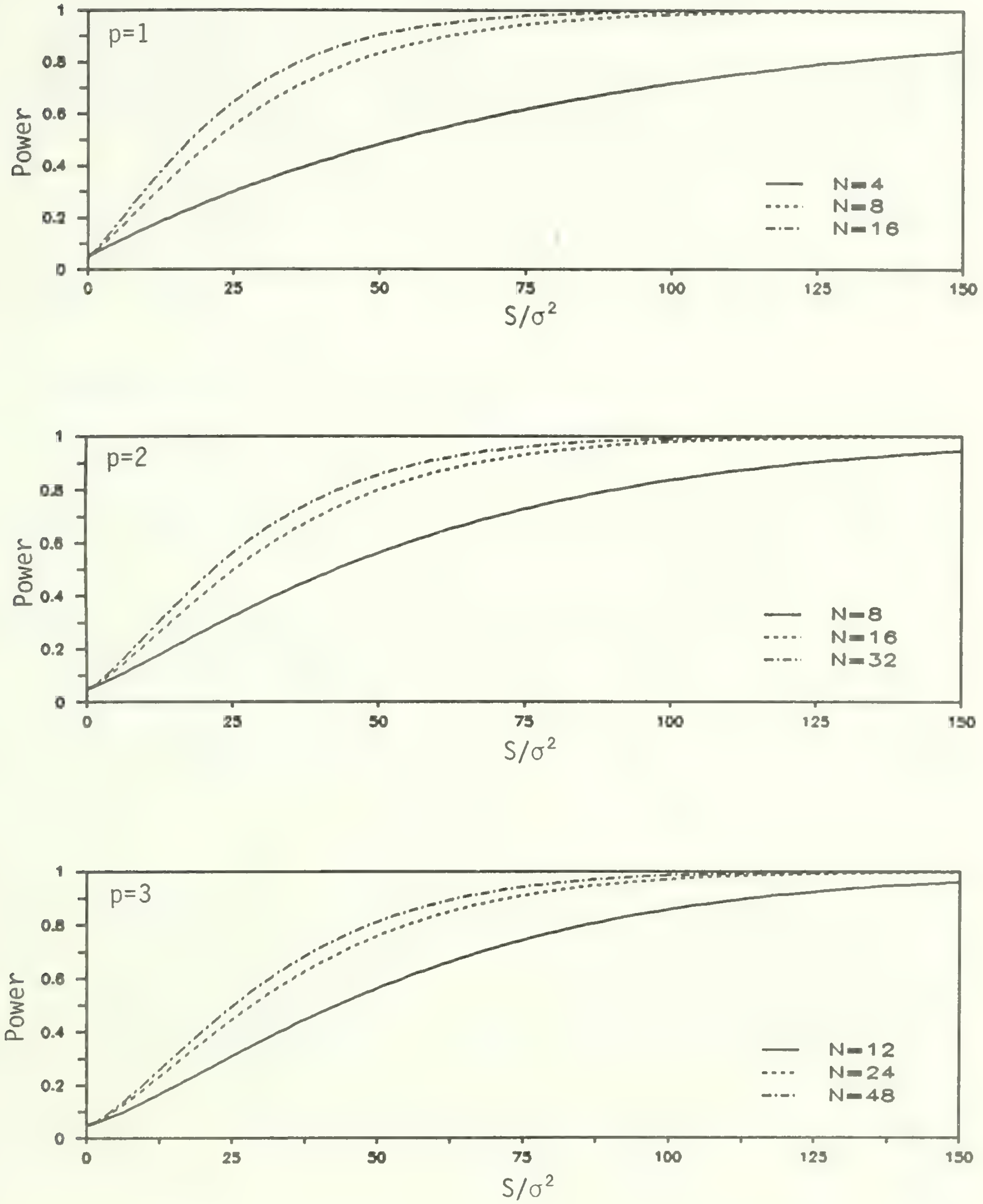

Figure 1. Power curves for the linear model F test for $\alpha=.05$ (p=number of model parameters and N=sum of sample sizes for both data sets).

The effects of nonlinearity on the power of the F test for comparing regression curves were investigated by simulating comparisons for each of the following models:

Allometric: $\hat{Y} = b_1 X^{b_2}$; $b_1=1.5$, $b_2=2.$

Negative exponential: $\hat{Y} = b_1 \exp(-b_2/X)$; $b_1=100.$, $b_2=10.$

Weibull: $\hat{Y} = 1 - \exp(-b_1 X^{b_2})$; $b_1=.000000095$, $b_2=3.8$

Chapman Richards: $\hat{Y} = b_1[1 - \exp(-b_2 X)]^{b_3}$; $b_1=240.$, $b_2=.08$, $b_3=1$

The set of parameter values shown with each model produces curves similar to those in the literature (Figure 2).

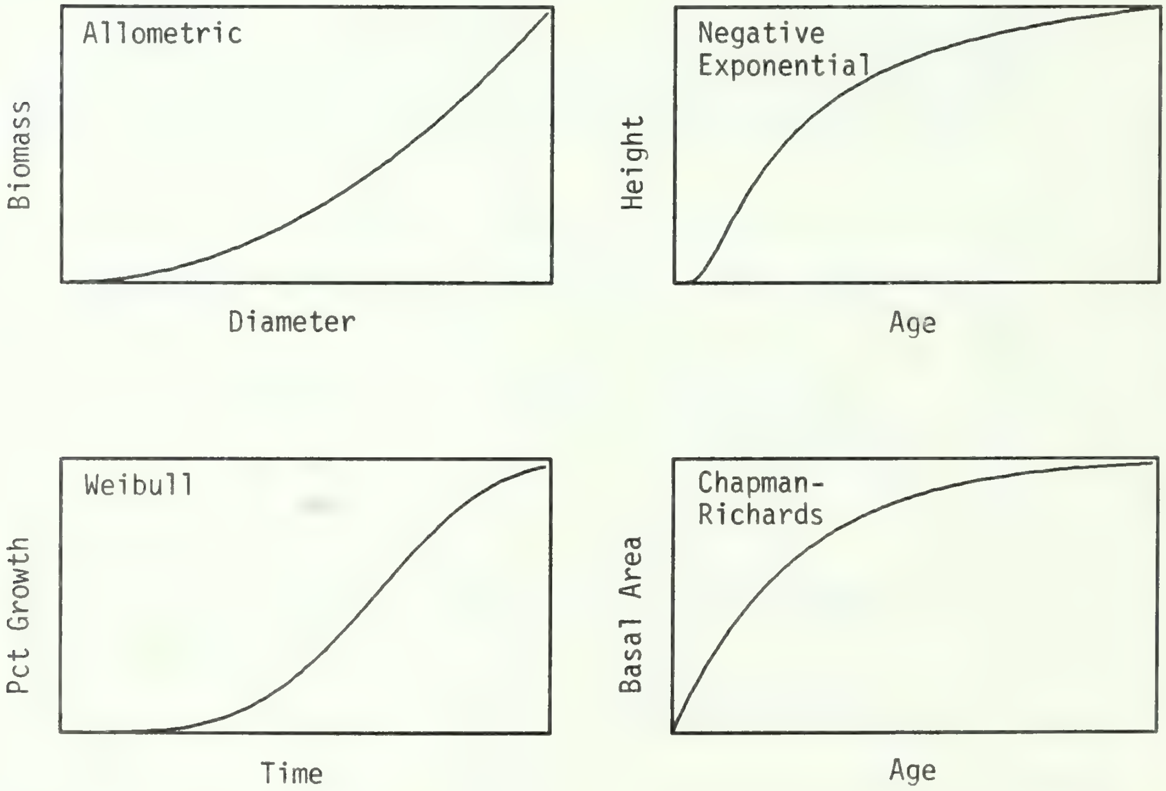

Figure 2. Nonlinear models.

For each nonlinear model, simulations were conducted for two sample sizes and for up to three different designs for values of the independent variable. Sample sizes equal to two and four times the number of model parameters were used for each of the two estimated regression curves to be compared. The primary design for each model and sample size had values of the independent variable approximately equally spread over its range. For the two-parameter models with the larger sample size, two additional designs were used. The first consisted of two replications of four points placed to yield expected values of 5.0, 35.0, 65.0 and 95.0 percent of the maximum value of the dependent variable. The second design consisted of four replications of two points placed to yield expected values of 33.0 and 67.0 percent of the maximum value of the dependent variable.

For each combination of nonlinear model, sample size, and design, simulations were conducted in four steps. First, the set of parameter values for each model was altered to produce two sets of true parameter values. Second, data sets were generated for each set of true parameter values by calculating a true value for the dependent variable for each value of the independent variable and then adding a randomly generated normal error with mean zero. Variances for the errors were selected to yield expected power under the linear model assumptions ranging from less than 0.5 to approximately 1.0. Third, nonlinear regression was used to estimate the model parameters for each data set. Finally, the two resulting regression curves were compared at the $\alpha=.05$ level using the F test based on the linear model assumptions. Fifty to one hundred simulations were conducted for each pair of sets of true parameter values. The statistical power of the test was estimated by the percentage of simulations for which the test indicated statistically significant differences.

NONLINEAR RESULTS

There were no detectable differences due to the placement of the design points for the two parameter models. Only one design was used for the three parameter Chapman-Richards model. For the negative exponential and Chapman-Richards models, there is a small loss of power for the small sample size when the expected power based on the linear model assumptions is below 0.5. No loss of power was discernible for the larger sample sizes for these two models. For the allometric and Weibull models, there is loss of power for both sample sizes (Figures 3 and 4). The loss is greatest when the expected power is small and tends to zero as the expected power approaches 1.0. The figure for the larger sample size for each model shows observations for all three designs.

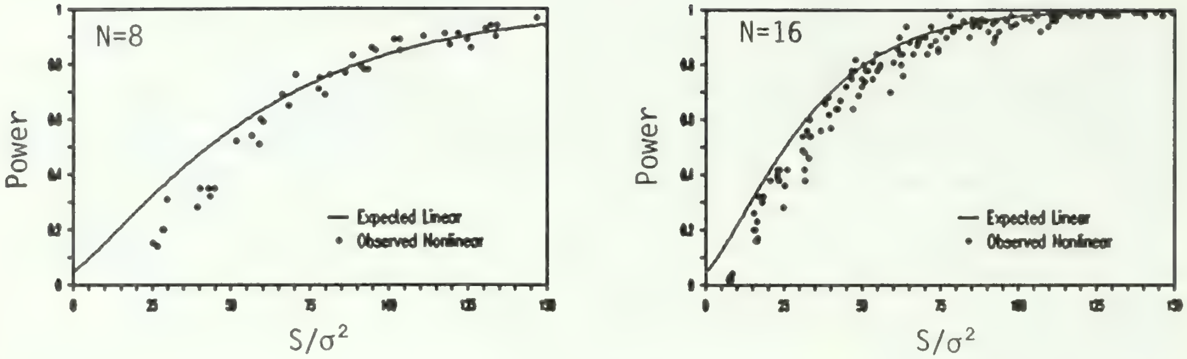

Figure 3. Power for the allometric model when testing at α=.05 for the linear model F test (N=sum of sample sizes for both data sets).

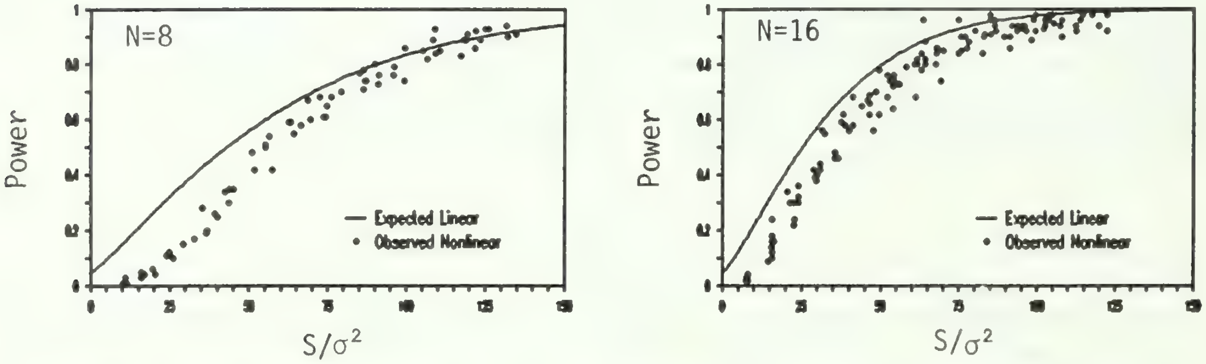

Figure 4. Power for the Weibull model when testing at α=.05 for the linear model F test (N=sum of sample sizes for both data sets).

CONCLUSIONS

The linear model power curves should be considered on a model by model basis for nonlinear models. The simulations indicate they are adequate for the negative exponential and Chapman-Richards models. For the allometric and Weibull models, there may be much loss of power when the expected power based on the linear model assumptions is low. However, if experiments are designed to produce statistical power greater than 0.8, which for most cases should be the minimum acceptable, the simulations indicate the power curves are adequate for these two models also. Future work in this area should concentrate on identifying models likely to exhibit reduced statistical power on the basis of an a priori estimate of their curvature. The negative exponential and Chapman-Richards models have both a linear parameter and a horizontal asymptote. In this regard they are nearly linear over a portion of the range of their independent variable. The allometric model has no asymptote and exhibits curvature over the entire range of its independent variable. The Weibull model, although it has asymptotes, also has two points of inflection. Thus, it is not surprising that the power curves based on the linear model assumptions are close to accurate for the negative exponential and Chapman-Richards models but quite inaccurate for the allometric and Weibull models.

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AN EVALUATION OF AN INVENTORY-PROJECTION SYSTEM: TRIM MODEL PREDICTIONS vs. FIA FIELD MEASUREMENTS IN NORTH CAROLINA

John R. Mills[1]

ABSTRACT. The TRIM (Timber Resource Inventory Model), which was used in the South's Fourth Forest study, received criticism because initial growth projections were much lower than expectations based on field measurements. An effort was made to evaluate TRIM using two successive Forest Inventory and Analysis (FIA) inventories of natural pine stands in North Carolina. The application of yield tables in TRIM can alter the results of regional timber-supply analysis. Projections using empirical yield tables derived from volume estimates predicted a deviation from the field measurements, but projections using yield tables derived from growth measurements were closer to the field reports. Results suggest that empirical yield curves do not represent aggregate stand growth. Growth-derived yields that are similar to normal yield curves may produce more accurate projections. Improvements to this modeling process will benefit the 1990 RPA National Timber Assessment.

INTRODUCTION

Predicting regional growth and yield for large aggregations of timber stands imposes many challenges on the modeling process. In the 1990 RPA Assessment, the USDA Forest Service will use a yield-table projection method to model the national timber supply. In this effort, the Timber Resource Inventory Model (TRIM) (Tedder et al. 1987) will carry timber inventories by stand age class and use yield tables to simulate growth and management for broad timber types. The techniques used by TRIM are not new, but the use of yield tables developed for broad timber types presents new problems that might be solved by old methods.

The first use of TRIM in regional analysis was for 12 southern states in The South's Fourth Forest (USDA in press). A problem developed in the early stages of this study when the growth projections for the Southeastern softwood inventory were 16 percent below current estimates based on measurements (includes Florida, Georgia, North and South Carolina, and Virginia). The projected inventory immediately ceased a long upward climb and dropped by 32 percent (16 billion cubic feet) in the first 25 years. These predictions were a reversal of previous trends, and they raised serious concern over the validity of TRIM's projection technique.

In an effort to address this criticism and investigate the model, TRIM was tested with field measurements from the 1974 and 1984 timberland inventories of North Carolina's natural pine type. This paper presents

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the findings of that study and its implications on TRIM's use of yield tables and the approach to normality for the 1990 RPA Timber Assessment.

YIELD TABLES

Yield tables that represent the expected growth and harvestable volume in timber stands have been used since the 18th century. Two classic types are "normal" and "empirical" yield tables. Normal yield tables represent volumes for natural fully stocked, unmanaged, and undisturbed stands. In contrast, empirical yields are generally derived from stands with a wider range of stocking, and they represent the average condition for a class of timber.

Yield tables that fall between the classic normal and empirical variety are often called "fully-stocked" and "well-stocked" yield tables. These yield tables are developed from a specific range of stocking densities that are above average but below normal. True normal stands are hard to find and a criticism of normal yields is that they are hard to apply to the majority of stands that are less densely stocked.

The yield tables developed for use in the South's Fourth Forest study were called empirical yield tables. These tables actually fall into the "fully-stocked" category because they were derived from fully-stocked stands as described by McClure and Knight (1984).

APPROACH TO NORMAL

The approach-to-normal concept assumes that, over time, understocked stands will naturally tend to approach a "normal" or fully stocked condition. This idea has received much support and documentation (among others, Chapman 1924, Chaiken 1939, Schumacher and Coile 1960). TRIM allows for an approach-to-normal function, which adjusts the relative stocking ratio (by age class) based on user-supplied parameters.

TRIM GROWTH AND YIELD

TRIM uses a yield table to project timber stand in the same way that Chapman (1924) described the technique for use with normal yield tables. The starting TRIM timber inventory is an aggregation of timber stands arrayed by 18 age classes. The inventory in each age class is calibrated to the yield table with a stocking ratio (stand volume over yield-table volume). The stocking ratio is adjusted by an approach-to-normal function each period and used with the yield table to calculate the stand volume in the subsequent age class.

Net growth in TRIM is the difference in net inventory volume from one period to the next. TRIM growth can be thought of as the mathematical derivative of the net yield curve. This kind of relationship between growth and yield can be called "compatible," under the definition of the term as used by Clutter (1963).

INVESTIGATION METHOD

The objective was to model as closely as TRIM input structure would allow, what was reported to have occurred in North Carolina's natural pine stands between 1974 and 1984. The Southeastern Forest Experiment Station, Asheville, North Carolina, provided the inventory data that included net growing-stock volume, growth, removals, mortality, and the associated acres by geographic location, owner, species, stand age, and stocking percentage. These data were converted into TRIM inputs based on a 5-year period. The Survey data was assumed to be accurate within respective sampling errors published in Sheffield and Knight (1986).

The criterion to evaluate projections was based on the difference between TRIM's 1984 estimate of inventory and the field-measured 1984 inventory. Successful model estimates were those that came within the sampling error surrounding the field measured value. TRIM projections were assumed to contain the same amount of error as field measurements; marginal projections were those in which the two error regions overlapped. Results outside this zone of overlap were classified as unsuccessful.

These criteria represent a rigorous test of TRIM because they address the critical function of the model: the accurate projection of inventories through time. Success or failure of projections in this study represents the success or failure of the yield tables to project inventories between two known points. Though apparently simplistic, this is the ultimate test for any model. The test was designed in an unbiased manner, with a minimum of TRIM inputs, using conventions followed by the South's Fourth Forest study (for more detail see Mills (1987)).

Part of this investigation was to examine the effects of data aggregation by site class. TRIM inputs were assembled for simulations under two basic formats. Natural pine was aggregated into three site classes in one set of projections and into one aggregate site class in another. Site class was a proxy for productivity as defined by McClure and Knight (1984). If projections using the two aggregation schemes both met the same criterion described above, I concluded that the projection method was insensitive to site-class aggregation. This entire procedure was duplicated by with the natural pine type on nonindustrial private (NIPF) ownership in Survey Unit 3 (North Carolina's Piedmont region).

Empirical yields were derived by plotting the average volume per acre by age class of fully stocked natural pine stands (100-132 percent FIA stocking, see McClure and Knight 1984) and running a freehand curve through the points. These yields were very similar to those originally developed by Knight for the South's Fourth Forest.

An alternative set of yield tables was developed from the net growth data on the inventory-plot records. These were called growth yield tables because they represented the summation of growth per acre across the 18 age classes. Growth and empirical yields looked quite similar to about stand age 35, when the empirical growth rate began to decline rapidly. After 35, the growth yields also showed declining growth but the decline was slower. By age 90, the volumes of some growth yields were over 45 percent higher than their empirical counterparts.

In each projection period, TRIM used the following linear form of an approach-to-normal function to adjust the volume stocking of the inventory by each age class:

$$SR_{i+1} = (a * SR_i) + b,$$

where: SR = stocking ratio in period i;
$a = 0.90$; and
$b = 0.10$.

ACREAGE SHIFTS

An added difficulty of this test of TRIM was the fact that simulations had to model a 1.2 million acre (19-percent) decline between 1974 and 1984. The Survey data documented a 22-percent decline in NIPF natural pine acreage in Survey Unit 3. Acre shifts also occurred among site classes. Acreage losses resulted from type changes brought about by partial cutting, cutting followed by artificial regeneration, and from land-use changes (Sheffield and Knight 1986).

REMOVALS

Over half of the state's 1974-1984 natural pine harvest came from acres that had shifted out of the natural pine type by 1984. All the removals in these TRIM simulations represented land clearing with no partial cutting (commercial thinning, selective cutting, or high grading). The Survey data showed that partial cutting amounted to 8 percent of the total removal; it was therefore not simulated in the projections, which would have required more time and possibly introduced more error into the process. All cut acres either returned to the first age class for regeneration or moved out of the timber base to represent land use or type changes.

PROJECTION RESULTS

The empirical yield tables failed to project accurately the inventories either for the state or the survey unit. The 1984 state-inventory projection was 22 percent below the reported figure; by the survey unit, the difference was 10 percent. Projected growth for the state was 35 percent below the measured growth and at the survey unit, 28 percent below what was recorded (see Table 1).

The growth yields produced successful projections for Survey Unit 3 but were unsuccessful for the state. They produced an average of 35 percent more growth for the state and about 24 percent more growth for the survey unit.

Subsequent projections were made in which the harvest was reduced to observe the effects on the projections. Harvests were reduced by 25 percent for the state. The large reduction was based on the desire to balance the growth-drain equation (1974 inventory + growth - removals = 1984 inventory). In this scenario, the growth number was assumed correct and the removal rate was overestimated. At the survey unit, harvest was reduced by 10 percent to represent the lower bound of sampling error surrounding the rate of harvest. Even with these reductions of removals, all projections using empirical yields were unsuccessful, but all projections using growth yields were successful.

Table 1. TRIM projections[a] for the natural pine type in North Carolina.

(net cubic feet - millions)

	Empirical yields		Growth yields	
Harvest	Growth	Inventory	Growth	Inventory
3,402	2,036 (-34.9%)	6,179 (-22.3%)	2,734 (-12.5%)	6,877 (-13.5%)
2,540	2,032 (-35.0%)	7,036 (-11.5%)	2,808 (-10.1%)	7,814 (- 1.7%)

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[a] Harvest and growth are 10-year totals. The numbers in brackets are percents by which 1984 projected values differed from target values.

DISCUSSION

These results indicate that (fully-stocked) empirical yields used in TRIM failed to project the changes in inventory measured in the field. Two aspects of the problem are associated with these empirical yield tables. First, they failed to project the measured growth and second, they failed to project the measured inventory volume. The first is a measure of change over time and the second is a measure of condition at one time.

Davis and Johnson (1987) suggest that problems with empirical yields of the kind observed here might be caused by underestimating stand mortality in the field. They argue that accurately measuring the mortality that occurs between successive plot measurements is difficult, and as a result net growth may be inflated. Empirical yields would not project the measured growth, but they may still project inventory volume accurately.

But what if the stands are growing faster than the empirical yields indicate? In addressing this question, Davis and Johnson (1987) argue that insects, disease, and fire periodically reduce stand volumes. All past epidemics of mortality affect the current condition of a timber stand. Thus, the flattening of an empirical yield curve may reflect past volume-reducing setbacks. A high growth rate recorded on some of the older stands may be a result of recovery from setbacks or a period of stagnation. Then empirical yields will underestimate both growth and inventory volume.

This second argument may best explain the failure of the well-stocked empirical yields in this test. Natural pine stands in North Carolina are subject to insect infestations, wildfire, disease, and the effects of weather, such as wind and ice storms. They are also subject to partial cutting such as commercial thinning, selective cutting, and high grading. Between 1974 and 1984, field measurements indicate that about 23 percent of the natural pine acres were disturbed by natural phenomena or partial cutting. The fully-stocked stands used to develop the empirical yields accounted for 45 percent of all natural pine acres in North Carolina. This rate of disturbance, combined with the large proportion of plots used for yield development, shows clearly that the effects of past disturbance are represented in the empirical yield tables.

Can we have confidence in growth yields used for stand projections? The results show that growth yields projected the measured changes in inventory much better than the empirical yields. Yet they too failed in the initial statewide projections and never did project the Survey-reported growth. Growth (like volume) is influenced by such things as weather and disease patterns, and changes in management practices (Knight 1987). Between 1974 and 1984, the average growth per acre derived from field measurements declined by 15 percent. Will calibrating TRIM with only 10 years of growth data bias a 50-year projection?

Since we must make assumptions about the future, stand growth is probably a better indication of stand trajectory, at least in the short term, than is current volume. An increase in average volume per acre appears to have occurred across all age classes in North Carolina (Figure 1). This increase corresponds much better to the trend of the growth-yield curve than it does the empirical volume curve. It is not known if this upward trend will continue, but yield tables in TRIM should at least be able to project measured trends.

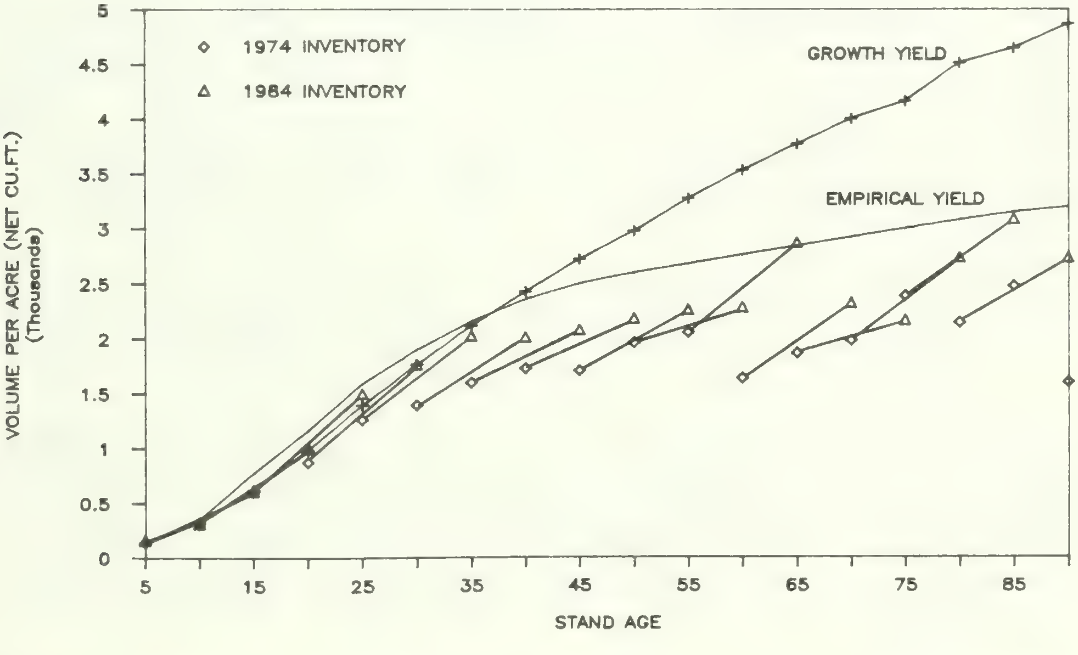

Figure 1. Average volume per acre of North Carolina's natural pine type in 1974 and 1984 plotted with the average-site yield tables used in TRIM projections. Lines connecting the inventory points represent the apparent 10-year inventory trajectory.

In developing yield tables for the RPA Assessment, the same relation between well-stocked empirical yields and growth yields found in North

Carolina was also found in California, Oregon, and Washington. In these other regions, growth per acre reported in the older age classes exceeded the statistically derived (fully-stocked) empirical yield tables. This finding is important because the data were for different species, and in different geographic regions where the survey techniques were different.

Another approach to the modeling problems described here is to use published normal yield tables (if available). The study done for North Carolina concludes that normal yield tables with the appropriate approach to normal function would have provided the best results. In a test of TRIM on jack pine in Wisconsin, Leary and Smith (in review) found that projections based on near-normal yield tables were in close agreement with FIA growth measurements from permanent plots. They used yield tables developed in 1938 from undisturbed plots and calibrated a polynomial form of an approach to normal function to use with TRIM. Their TRIM growth projections matched independent growth estimates derived from remeasured permanent plots.

CONCLUSIONS

Use in TRIM of empirical yields developed from inventory volume will not adequately represent stand growth potential. These yields present a picture of current stand condition that does not indicate future stand development.

Yield tables developed from growth data were more successful in projecting inventories. They were derived from a full range of field growth measurements and should be considered compatible yield tables for TRIM projections. Growth yields are being used in the RPA for California and the eastern Oregon and Washington timber types. (An independent investigation is being conducted to derive the yield tables to represent western Oregon and Washington.)

An even more desirable approach would be to use normal yield tables, where available, with TRIM. The model is able to calibrate the inventory to the yield table, which averts the problems associated with their application to less densely stocked stands.

Current projections made with TRIM for the South's Fourth Forest have been improved through revisions to both the structure of TRIM and the parameters used. Model revisions include improvements in handling area shifts, the use of yield tables reflecting better timber-management practices, and the implementation of growth-yield tables for natural pine. Growth has also been increased by adjusting the approach-to-normal function.

Progress has been made, but problems remain that need to be addressed in, and beyond, the 1990 Assessment. Normal yield tables hold promise, but their availability for aggregations of pure species into forest types is limited. The approach-to-normal equation can have any form in TRIM, but like yield tables, its proper application to aggregate stands is not well understood. The harvest mechanism in TRIM also needs investigation. Except when thinning, the model harvests the average volume per acre in an age class. When the total harvest volume is proportioned across a range of age classes (as it was in this study) TRIM may be cutting too many acres to achieve the requested volume. If so, TRIM is too rapidly shifting stand structure to younger age classes by the harvest and regeneration of too many acres. Current research is addressing partial cutting, and a subroutine is being added that may help improve the harvesting process.

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A MONTE CARLO COMPARISON OF PROPAGATED ERROR FOR TWO TYPES OF GROWTH MODELS

H. Todd Mowrer[1]

ABSTRACT. A Monte Carlo technique is used to simulate errors in input variables at increasing levels of sampling intensity. These errors are propagated through five 10-year projections by two growth and yield models. Comparison of the response surfaces indicates that the more complex diameter distribution model estimates the same stand average values with less precision than the whole stand model. Similarities in silvicultural assumptions, calibration, and predictive technique allow differences to be attributed to model resolution.

INTRODUCTION

One objective of growth and yield modeling is to quantify stand development for a particular forest type at a desired level of resolution. This implies several decisions inherent in model development: silvicultural assumptions about stand classification and development, quantitative judgments about calibration and predictive technique, and reconciliation of these requirements with desired model resolution. Deliberate decisions are made about these elements, but often the precision of resulting model estimates is not considered.

This study compares two growth and yield models, one predicting stand average values directly from regression equations (Edminster and Mowrer, 1984), and the other based on a normal probability distribution of stems per acre across 1-inch diameter classes (Mowrer, 1986). For both models, the precision of projected stand variables is calculated for multiple 10-year projections using a Monte Carlo technique to estimate the propagated variance due to initial variability in model input variables. This paper examines the relationship between model resolution and precision.

RESOLUTION

In order to properly compare the precision of alternative modeling approaches, similarities and differences between models must be established. The decision elements discussed here form a framework for this comparison. The terminology involved in silvicultural and calibration decisions has been well defined in the literature (Moser, 1980, Trimble and Shriner, 1981) and warrants no additional elaboration. In the past, however, resolution has been used as a blanket term without reference to the various factors that it encompasses. The degree of

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resolution can be classified by examining spatial, temporal, and structural relationships in the modeling process.

Munro (1974) provided the terminology for categorizing spatial resolution, ranging from whole stand models predicting stand average values at one extreme to individual tree models at the other. Even finer spatial resolution may be obtained from biological models quantifying microprocesses of tree component growth. In between these extremes lie diameter distribution models and diameter class models.

Temporal resolution, or the time period encompassed by a single model projection, is to some degree dependent on the spatial resolution of the predicted variable and may range from a decade to a fraction of a growing season. Estimates at finer levels of spatial and temporal resolution may be aggregated to provide estimates at a coarser level.

Structural resolution is the complexity or intricacy of the internal calculation process. This is primarily reflected by the number of driving variables in the model. For the purposes of this paper, the vector of driving variables is defined as the minimum subset of model variables that must be initialized to begin model projections. If periodically updated at each projection, driving variables are only a function of past values. Secondary variables are estimated from current values of driving variables and/or other secondary variables. Increased structural resolution generally accompanies increased spatial resolution. However, a range of structural complexity is possible within each level of spatial resolution. Daniels (1981) developed a system of structurally related growth models, providing numerically consistant estimates at different levels of structural and spatial resolution.

PRECISION

The degree of reliability with which model variables are predicted is commonly measured by the mean squared error, consisting of the variance plus a bias-squared term. Many model validations estimate bias by comparing model projections with repeated measurements from permanent growth plots. Mowrer and Frayer (1986) introduced two methods to estimate the variance associated with repeated periodic projections. A Monte Carlo technique was used to estimate the effect of external variation in initial values of driving variables on volume estimates by the same diameter distribution model after a single 10-year projection. The method of statistical differentials was used to internally calculate estimates of the propagated error based on the same initial levels of Monte Carlo variation. After a single 10-year projection, variance estimates from these two methods coincided within the bounds of the analysis.

METHODS

THE GROWTH MODELS

The two models are nearly identical in three of the decision elements listed above: silvicultural assumptions, quantification technique, and temporal resolution. Both models predict growth and yield of pure, even-aged stands of aspen (Populus tremuloides, Michx.) in the central Rocky Mountains. For this comparison, both models simulate development of naturally occurring, unthinned stands of aspen subject to non-catastrophic mortality.

A subset of the whole stand model calibration data exhibiting a normal probability distribution of stems per acre across 1-inch diameter classes was used to calibrate the diameter distribution model. Both models make empirical estimates of the 10-year periodic change in each driving variable based on linear regression techniques, providing compatibility in calibration technique and temporal resolution.

Obvious differences exist in spatial and structural resolution, however. In spatial resolution, one model operates at the coarsest or whole stand level, and the other by diameter distribution at the next finer level. These result in differences in structural resolution, with the whole stand model requiring only four driving variables to initiate periodic projections: quadratic mean stand diameter, stems per acre, site index, and stand age. Secondary variables (average stand height, basal area per acre, and gross total cubic foot volume, gross merchantable cubic foot volume, and Scribner rule board foot volume on a per acre basis) are estimated directly from current stand conditions.

The diameter distribution model requires five driving variables to be initiated: stems per acre, average stand age, and site index, with arithmetic mean stand diameter and associated variance defining the normal probability distribution. The same secondary variables are calculated in the diameter distribution model, but by aggregation of individual estimates across 1-inch diameter classes rather than by direct estimation.

MONTE CARLO TECHNIQUE

The Monte Carlo simulation of initial values for model driving variables (described in detail by Mowrer and Frayer, 1986) serves several purposes. A multivariate normal distribution was used as a basis for repeatedly simulating samples from the selected stand. The resulting covariance relationship between driving variables in successively simulated samples mimics the existing relationship in repeated field samples and provides a realistic reflection of their relative variability.

In each of 30 replicates, 27 sequential samples were simulated from the multivariate normal distribution. Twenty-six cumulative means for the vector of driving variables were calculated over all previous sample values for the second through the twenty-seventh successive Monte Carlo realization. Independent random starts were used for each of the 30 replications.

In a previous study (Mowrer and Frayer, 1986), cumulative means were simulated up through 100 point samples. Little change was observed after 20 simulated point samples, so a sequence of only 26 cumulative means were calculated in the current study. Similarly, replication levels up to 100 were previously explored, with little change above 30 replicates for each of the 26 levels of sampling intensity.

These 780 sets of values for the driving variables were used to initiate five 10-year projections by each model. At the initial time period (projection zero) and at each successive period (projections one through five), the mean, variance, and coefficient of variation (c.v.) were calculated for selected driving and secondary variables across the 30 replicates at each of the 26 cumulative sample means. Identical processes were applied to both models, except that different mean vectors and covariance matrices reflecting differences in driving variables were used in the Monte Carlo simulations.

RESULTS

Figures 1a through 1d show response surfaces for the two growth and yield models across 26 cumulative sample means and five 10-year projections. Sampling intensity increases from left to right across the x-axis. The y-axis reflects increasing projection length from front to back with initial variation at 10-year projection zero, coincident with the x-axis. The coefficient of variation (the standard deviation times 100 percent, divided by the mean) for each stand variable is measured on the z-axis.

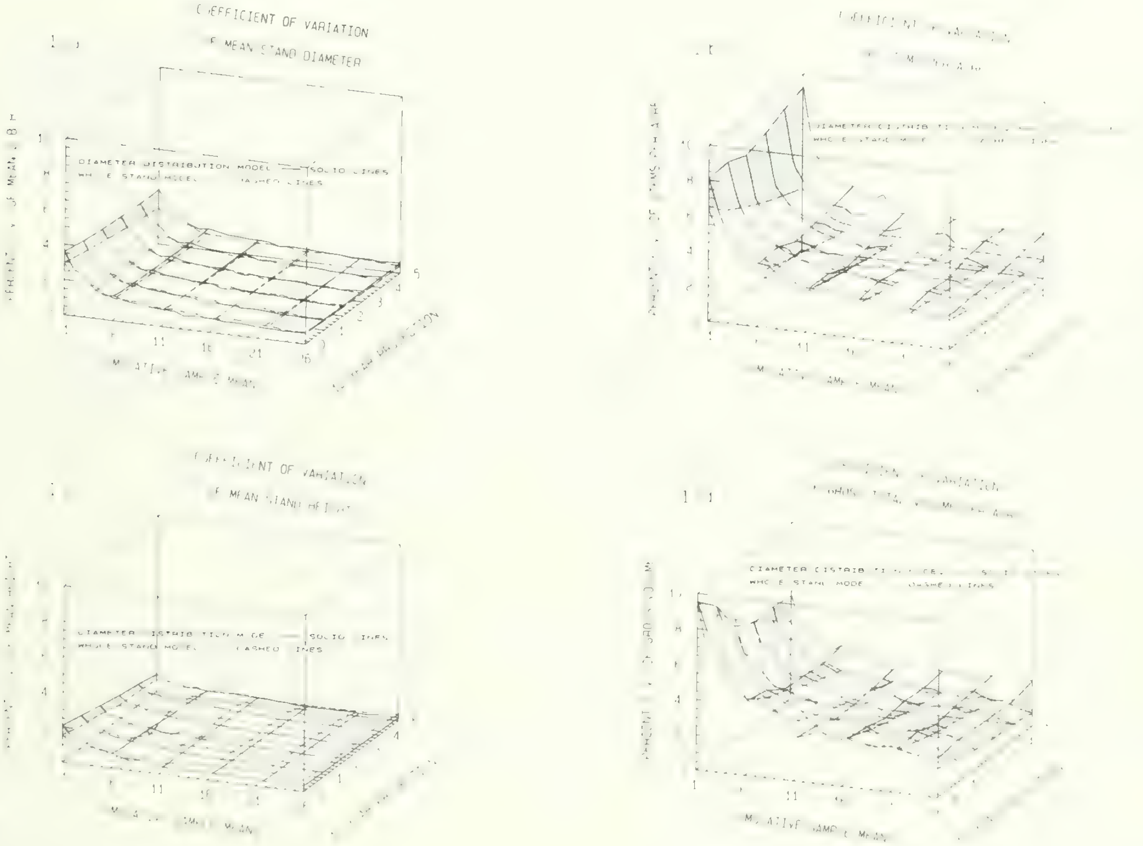

Figure 1. Coefficient of variation of propagated error for a diameter distribution model (upper response surface) and a stand average model (lower response surface) for initial and predicted (a) mean stand diameter, (b) stems per acre, (c) mean stand height, and (d) gross total volume in cubic feet per acre.

In general, the response surface for the diameter distribution model lies above that of the whole stand model, indicating less precise estimates. The vertical planes between the two response surfaces have been shaded every five cumulative point sample means to highlight variability over increasing projection length. Only the areas in each plane are shaded where the propagated error of the diameter distribution model exceeds that of the whole stand model.

DRIVING VARIABLES

Figure 1a shows the coefficient of variation of mean stand diameter. Increasing the number of point samples in successive cumulative means results in a decreasing c.v. of initial mean stand diameter, as shown across the front of the figure, for 10-year projection zero. Little reduction in variability occurs after the eleventh sample mean is included. Predictions by the diameter distribution model show greater variability than those for the whole stand model, particularly for fewer cumulative point sample means. At these higher levels of variability in input values, there is a slight increase in the c.v. for the diameter distribution model across 10-year projections, while the whole stand model remains relatively constant.

As might be expected, Figure 1b shows a greater difference between the response surfaces for variability in initial and projected stems per acre. Initial levels of variation (at 10-year projection zero across the front of the figure) are an artifact of the variability inherent in the selected plot. The divergence between response surfaces over longer projection lengths reflects an increasing difference in the relative magnitudes of the errors propagated by the models.

While a downward trend in propagated error with increased projection length is again reflected in the whole stand model response surface for stems per acre in Figure 1b, a substantial increase in error occurs for the diameter distribution model. These differences increase more rapidly for higher levels of initial variability in stems per acre, as shown by the relative magnitudes of the shaded areas from right to left.

SECONDARY VARIABLES

Figures 1c and 1d show the propagated error for secondary variables in both growth and yield models. The method of calculation differs between models in that the variables are predicted by single estimators in the whole stand model, while they are the result of summation over the normal probability distribution of stems per acre by 1-inch diameter classes in the diameter distribution model.

Even less variability is apparent in the coefficient of variation of mean stand height than for mean diameter, as shown in Figure 1c. While the response surface of the whole stand model lies slightly above that of the diameter distribution model for lower levels of initial errors, both surfaces are relatively parallel and indicate little difference in propagated error across the range of cumulative sample means and 10-year growth projections, despite the difference in the method of calculation.

Part of this lack of propagated error is due to a paucity in initial value variation from the Monte Carlo simulation.

The cumulative effect on volume estimation of propagated errors in diameter, height, and stems per acre is seen in Figure 1d. Propagated errors from the diameter distribution model are still greater than those from the whole stand model, but the overall effect of the mixing of the various sources of error is apparent. For increasing projection length, there is a general decline in c.v. for the whole stand model. At higher levels of initial variation, the diameter distribution model shows a decline in c.v. over the first two to three projection periods, and then an overall increase. At higher sampling intensities (above 11 cumulative means), there is a consistent increase in propagated error for the diameter distribution model.

While the propagated error for both basal area per acre and gross total cubic foot volume per acre were analyzed, only the response surfaces for total cubic foot volume per acre are presented. Calculations for basal area were dependent on the square of diameter and stems per acre, while gross total cubic volume involved an additional height term. The small amount of error propagated by the height calculations created only a slightly different propagated error response between gross total volume and basal area. Gross merchantable and board foot volumes were not compared, since the Monte Carlo process caused fluctuations at the trigger levels of stem diameter for the whole stand model, resulting in unreliable fluctuations in these volume estimates.

DISCUSSION

The variation introduced in the initial values of the driving variables provides the main source in Monte Carlo error propagation. A comprehensive estimate of propagated error should contain not one, but four, sources of variation. Of these, the Monte Carlo method totally ignores two.

Since these models use linear regression estimators, components of these equations represent a major pathway for error propagation. There are three of these components: regression variables, regression variable cross-products, and estimated regression coefficients.

The Monte Carlo technique only propagates errors in regression predictor variables and their cross-products. However, variance associated with regression coefficient errors is totally ignored in the Monte Carlo process. In order to incorporate variability in these elements, a similar Monte Carlo technique would have to be applied to the mean vectors and covariance matrices associated with the estimation of the regression coefficients. This would increase propagated error estimates for both models.

In reality, there are differences between the theoretical and actual distribution of stems per acre for the diameter distribution model. Since only stand average values are simulated here, it is assumed that all stands conform exactly to a normal probability distribution of stems per acre across diameter classes. This is seldom, if ever, true. For plot data comprised of tree lists, a residual mean-squared error reflecting the difference between actual and theoretical values should be included. This component is not reflected in these simulations, and would increase the error for the diameter distribution model relative to that of the whole stand model.

A more qualitative aspect of model construction is the selection of the "correct" or "best" predictive relationship. It is doubtful that empirical linear regression approximations of biological functions meet this paradigm. The large amount of error propagated by the mortality function in the diameter distribution model implies that this relationship could be improved. However, comparing models with the same internal estimation technique allows a more valid comparison of the effect of model resolution on the relative magnitude of propagated variance.

While this procedure does reflect the variance relationships between driving variables, it does so only for the particular plot used as a basis for the simulation. In order to draw more general conclusions about model reliability, this procedure would be repeated for each plot in the calibration set.

CONCLUSIONS

The Monte Carlo technique provides a relative estimate of the errors propagated over repeated projections by the two models. The variability in inputs due to repeated sampling of a given plot provides a realistic setting for simulating the correlation between driving variables, and also provides a range of variance for evaluation of propagated error. However, it fails to incorporate the effect of the variance associated with estimated regression coefficients.

Application of this technique is relatively straightforward, requiring more intensive use of computer resources than knowledge of the internal mechanisms of the growth and yield model to be evaluated. Analysis of the results, however, is enhanced by an understanding of the projection techniques within the model.

The procedure presented here does provide a subjective comparison of differences in errors propagated by the two growth and yield models. The high degree of similarity between the two models in all other aspects allows differences in propagated error to be attributed to changes in spatial and structural resolution. While providing diameter-specific product information, the diameter distribution model predicted the same variables with less precision than the whole stand model. In this analysis, a price in predictive reliability was paid for the increase in spatial resolution from stand average to diameter distribution estimates.

This may well indicate a general loss in precision when additional information is estimated by more complex growth and yield models. In this case, the next generation of models should be structurally integrated to provide consistent estimates at different levels of resolution as Daniels (1981) suggested, providing flexible, efficient, and reliable growth and yield estimates at the appropriate level of resolution to meet management goals.

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VALIDATING FOREST GROWTH MODELS:
PROCEDURES DEFINED BY RESOURCE DECISIONS

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ABSTRACT. Validation of forest growth models should help both the user in assessing model reliability and the developer in formulating and improving subsequent models. Criteria defining acceptable model behavior depend in large part on the user's decision-making situation and on the characteristics of the forest being managed. However, emphasis on the user must not preclude the model developer; otherwise, opportunities for improving the forecasting capability may be lost. The Inland Northwest Growth and Yield Cooperative is developing techniques based on both user and developer interests to validate existing forest growth models in the Inland Northwest. A validation framework in the form of a decision tree contains three decision-making applications: scheduling harvests, updating inventories, and planning silvicultural investments. This framework helps define relevant data, criteria, and appropriate analysis techniques for evaluating model behavior. In addition, it may suggest important areas for further data collection and model revision. Components of this procedure are currently being undertaken by the cooperative.

INTRODUCTION

Forest growth and yield models are important analysis tools in almost any forest management decision process. As such, many researchers have spent considerable time and effort to develop the most reliable forest growth and yield models possible. One important aspect of any modeling process is, of course, some type of model validation. Many examples of specific forest growth and yield model validations (e.g., Daniels et al. 1979, Ek and Monserud 1979), validation statistics (e.g., Ek and Monserud 1979, Reynolds 1984), and general validation considerations (e.g., Buckman and Shifley 1983, Brand and Holdaway 1983) can be found in the forestry literature. After careful review of this literature, we conclude that validation logically depends on the decisions for which the model is to be used.

The Inland Northwest Growth and Yield (INGY) Cooperative is developing a forest growth and yield model validation process based on the needs and constraints of its membership. Two aspects of INGY are particularly relevant to the validation process contained in this paper. First, this cooperative, which comprises university, industrial, and governmental institutions operating in western Montana, Idaho, eastern Oregon,

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eastern Washington, and adjacent Canadian provinces, includes both users and developers of several models. Therefore, validation results need to be meaningful for both. Second, INGY goals and activities require that we not only ask, "How reliable are the current models?" but that we also ask questions about the reliability and range of the current data base. This allows us to decide what level of confidence should be placed on the validation as well as where future data collection and model revision efforts will be most useful.

The validation process currently under way in the INGY Cooperative requires specification of a validation framework that defines relevant data and criteria for acceptable model behavior, model sensitivity analyses, and statistical analysis procedures based on both model developer and user needs. The validation process ends with one of four outcomes for a particular decision:

1. Model is adequate.

2. Model needs revision using the available data identified in the process.

3. Data appear inadequate to evaluate model, and new data are required.

4. Model is irrelevant.

The first outcome provides the user with confidence to apply the model. The remaining outcomes influence the priorities of future efforts by the cooperative.

MODEL VALIDATION FRAMEWORK

The INGY model validation framework consists of two categories of variables that together provide the basis for evaluating model adequacy. The first category defines the management context and the second category the biological domain.

MANAGEMENT CONTEXT

Presented with a model that is purported to be worthy of use, a question often asked is: "Has the model been validated?" Because it is logically impossible to show a model to be valid, the implied question is: "Is this model adequate for my use?" To define the management context or "use," the INGY Cooperative has identified three basic forest growth and yield model applications: harvest scheduling, inventory updating, and evaluation of silvicultural investments. Within these applications, context is further described by whether comparisons are within or among stands or treatments, by time span, by initial stand conditions, and by frequency of decision. This is a detailed specification of the initial step of the validation process presented by Brand and Holdaway (1983).

Harvest scheduling refers to the use of growth models to generate stand volumes through time over a range of management regimes so that harvest levels can be estimated using techniques such as mathematical programming. Inventory updating is the use of growth models to estimate growth and mortality in a forest stand in the usually short period between the time a stand was last inventoried and the present. Estimated growth and mortality is used to update stand volume and other information without remeasuring the stand. Evaluation of silvicultural investments refers to using forest growth models to estimate the future yields of a given stand for different silvicultural alternatives. The alternative with the highest return consistent with management objectives is usually chosen as the appropriate silvicultural investment. It can also refer to the allocation of treatments among stands in a way that produces "highest" return for a given amount of capital investment. This somewhat limited list is consistent with our user group needs and not intended to suggest these are the only important applications for forest growth and yield models.

Figure 1 shows the characterization of the three INGY user applications (the decision trees are incomplete due to lack of space).

Four decision variables are important in evaluating model adequacy in the harvest scheduling application. When the time span is short, yield and present net value (PNV) should lead to similar model evaluations. However, for long time spans, both yield and PNV are necessary due to differences introduced by discounting. Yield or PNV are appropriate for within-stand and within-treatment comparisons, but differences in yield or PNV are appropriate for the remaining situations. Notice in the figure that there are 48 possible managerial contexts. Each context has its own appropriate decision variable, confidence levels, specification for bias and precision, and analysis procedures.

The evaluation of silvicultural investment application is similar to the harvest scheduling application but has some important differences. There are 36 possible management contexts associated with this application due to omission of within-stand and within-treatment situations. This omission and typical financial evaluation criteria lead to only one decision variable, which is difference in PNV.

Only three management contexts exist for the inventory updating application. Inventory updating involves short time spans from existing stand conditions and only within-stand and within-treatment situations. Therefore, the only possible management contexts in this application are associated with repeatability of the decision (i.e., the estimate). The decision variable in the case is different from the other applications. Here, root mean square error (RMSE) is an appropriate decision variable due to inventory reliability requirements.

BIOLOGICAL DOMAIN

The biological domain also categorizes the validation framework according to several variables that are important in the prediction of forest growth. The variables used to determine the categories are habitat series, geographic location, slope, aspect, elevation, species, age, site index, and relative density (Byrne et al. 1987, Arney and Reimer 1987). Within these categories, data available for validation can be compared to the biological domain of the user's application. A scarcity of data leads to the third of the four possible outcomes of the validation process.

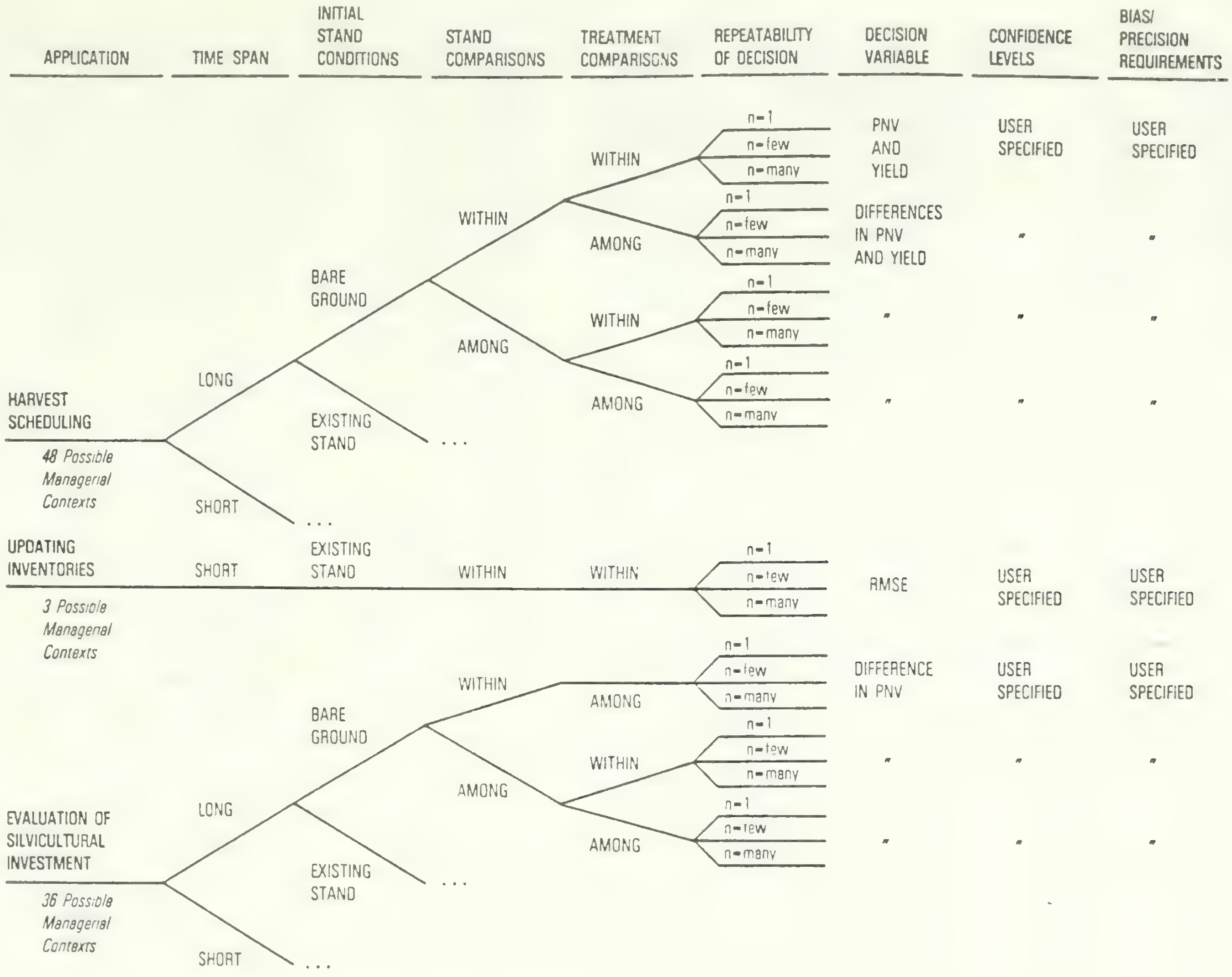

FIGURE 1. Decision tree defining managerial context for harvest scheduling, inventory updating, and evaluation of silvicultural investments in the INGY Cooperative's validation process.

MODEL SENSITIVITY

Model sensitivity analyses are used in the validation process to determine:

1. whether measurement errors in an existing data set are adequate to include these data in this validation analysis (Hamilton 1987);
2. relative contribution of measurement and sampling errors to total response error;
3. relative effect of errors in model components such as ingrowth, accretion, mortality, etc. (Stage 1985, Patterson and Stiff 1987 elsewhere in these proceedings).

ANALYSIS PROCEDURES

Although the diversity of managerial and biological contexts for a validation analysis precludes a "once and for all" analysis, certain attributes of model performance can be estimated in advance for subsequent evaluation of model adequacy. These attributes are sensitivity of model results to treatments and omitted variables, model bias and precision, and relative effect of model component errors on bias and precision.

The result of the analysis is either the first outcome (model is adequate), the second (model needs revision), or the fourth (model is irrelevant). Managerial context controls choice of test procedures and helps the user specify confidence levels. Model sensitivity analyses and data from the relevant biological domain provide parameters used in the testing. The information needed for these tests include:

1. Bias of the model for the selected decision variable, evaluated for the treatment, site, and stand conditions relevant to the decision.
2. Variability of the decision variable produced by the model.
3. Specification of yes-no decision point for model adequacy.

BIAS

Estimation of the bias requires the decision variable be the result of a process that includes randomization. When the decision variable is yield or PNV, the randomization must have controlled the choice of plot locations. When the decision variable is a difference, the randomization inherent in the experimental design may suffice. If a random sample of locations is available, the model should be adjusted for use by "modeling the bias" and thereby removing the bias from the model. Then, the standard deviation of residuals can be used in calculations of model variability. If a random sample of the population is not available, then the bias cannot be removed and the mean-square error, which includes the squared bias, should be used in calculations of model variability.

MODEL VARIABILITY

Residuals between observed yields and model estimates include effects of measurement and sampling errors in both starting and ending values, effects of plot size and length of projection, and variation due to the growth process itself. Of these sources, the measurement and sampling error components should be removed, using the results of the sensitivity analysis (Stroud 1972). Then, the residual variability is scaled to the spatial extent of the stands to which the model will be applied (Smith 1938, Stage 1987 elsewhere in these proceedings).

For the managerial contexts involving a choice among alternatives, the relevant measure of variability includes not only the variability inherent in the output of the model, but also includes an estimate of the covariance between the errors for each alternative. Of all the data needed for these analyses of model adequacy, the covariances between residuals are the most likely to be missing. The only sources of such information are likely to be replicated experimental studies comparing treatment alternatives. Lacking such data, the analyst may have to subjectively estimate the correlations. For example, correlation between two alternatives involving the same species growing in similar stand structures would be expected to be higher than for alternatives comparing a plantation yield with a natural stand yield on the same site. This correlation, in turn, would be higher than the correlation for a comparison between two stands of different species or structures growing on different sites. Note that each of these three alternatives correspond to different "twigs" on the tree of managerial contexts. Because of the different covariances, the same model might turn out to be adequate for some contexts, but not for all.

DECISION POINT

Adequacy of a model for management applications that involve a decision between two discrete alternatives can be evaluated in terms of the probability of a wrong decision. To do so requires knowing the "break-even point" for the particular decision. Because the decision variable is a difference, we assume that zero is the "break-even point."

The situation is not quite so simple for applications in which the decision variable is yield or PNV. In this situation, the user must provide the maximum bias and precision to be considered acceptable. This limit will be chosen depending on the manager's perception of the cost of being supplied with an estimate in error to various degrees. Hamilton (1979) has described the considerations involved in establishing such loss functions. Lacking information in the form of a loss function and assuming equal costs between models, managers can specify the bias and precision of the model that they have been accustomed to using for similar decisions in the past. Presumably, a new model is adequate only if it can out perform its predecessor for the same costs.

TEST PROCEDURES

For management contexts in which the decision variable is a difference between discrete alternatives, the final step in the analysis is to apply the tests described by Freese (1960) with further elaboration by Reynolds (1984) to reach a decision on accepting the model. In these procedures, the value of required accuracy is four times the squared mean of the decision variable.

For the few, but important, managerial applications in which the decision variable is yield or PNV, choice of the test procedure depends on whether the decision point information is assumed to be absolute, without error, or whether the information is statistical. In the former case the Freese/Reynolds tests are used. In the latter case, tests comparing biases and variances such as are described in standard statistical textbooks are applicable.

CONCLUSIONS

The validation process we describe differs from common practice in several respects. Foremost is recognition that the user's applications play a major role in molding the analysis, and we provide a means to determine appropriate managerial contexts for these applications. Second, certain analysis procedures were developed to enhance the modelers ability to use the validation results to improve subsequent models. Next is recognition that managerial contexts in which decisions involve differences rather than yield or PNV per se call for different test procedures. In these cases, we specify how model accuracy requirements can be derived from the average values of the decision variables. Furthermore, we point out that correlation of prediction errors, sensitivity of the model to measurement and sampling errors, and sizes of the target stands must be considered when calculating variability of the decision variable.

Finally, although defining the management application increases the specificity of the analysis, major portions of the validation process are common to all applications. Hence, much of the analysis can be performed in advance. Furthermore, because of the increased specificity, we believe that extrapolation to cases where data for validation are insufficient can be more reliable.

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THREE-DIMENSIONAL REPRESENTATION OF STAND VOLUME, AGE AND SPACING

K. L. O'Hara and C. D. Oliver

Abstract. Competition-density theory, the -3/2 law of self-thinning, and stand age can be incorporated into a three-dimensional surface to represent forest stand growth. The three axes are trees per unit area, stand age, and mean tree volume. When viewed from three sides the model reconciles three relationships regarding stand growth: the competition-density effect and -3/2 law of self-thinning; the reverse-J shaped decline in density with increasing age; and the correlated curve trend of mean tree volume growth at different spacings with stand age. The three-dimensional surface represents an average level of standing volume (expressed as mean tree volume) for unthinned stands of a range of age and density. A similar three-dimensional baseline model can be constructed from the same information but with volume per area on the vertical axis instead of volume per tree.

Two three-dimensional surfaces were constructed with data simulated for a specific site quality from two Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) growth and yield models: Douglas-fir Stand Simulator (DFSIM, Curtis et al. 1981), and Tree and Stand Simulator (TASS, Mitchell and Cameron 1985). The three-dimensional surface facilitates visual comparisons between the two growth and yield models over their common range of age and density. Further quantification of a three-dimensional surface for forest stands will permit development of a standard or baseline level of volume growth from which to compare other growth projections as well as the growth and differentiation of actual stands.

INTRODUCTION

Comparisons of growth and yield models generally consist of one to one comparisons of growth and yield data for specific stand ages, densities and site qualities. Three-dimensional representations of mean tree volume growth, or stand volume growth, over stand age and density offer useful graphical approaches for comparisons of growth and yield models for specific site qualities. The models are an integration of competition-density theory, the self-thinning law, the reverse-J decline in density with age curve, and the correlated curve trend.

COMPETITION-DENSITY THEORY AND THE SELF-THINNING LAW

Studies of the relationships between density and mean plant size have provided useful information concerning biomass accumulation in plant populations. The competition-density effect, or the reciprocal yield relationship, describes the relationship of mean plant size and density

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in populations of a specific age (Kira et al. 1953; Hozumi et al. 1956; Shinozaki and Kira 1956). According to this relationship mean plant size is unaffected by density at low densities; mean plant size decreases curvilinearly with increasing density (on logarithmic coordinates) at intermediate densities; and mean plant size decreases with a -1 slope with increasing density at higher densities (Figure 1). The region of -1 slope is referred to as the zone of constant final yield (Hozumi et al. 1956) because biomass production per unit area is constant in the absence of mortality. Successive ages represented by reciprocal yield, or competition-density relationships, reach successively higher mean tree volumes; but the range of densities where mean plant size is unaffected by density becomes progressively smaller.

The self-thinning line (Yoda et al. 1963) defines an upper limit of mean plant size that forms a -3/2 slope with density when both variables are graphed on logarithmic coordinates (Figure 1). In contrast to the competition-density effect, the self-thinning line is independent of age, or stage of development, and site quality. Together the competition-density effect and the self-thinning line define successively later stages of development as having increasingly larger mean individual sizes, but the possible range of densities is decreased by mortality along the self-thinning line (Figure 1).

Applications of the self-thinning law to forest stands are common -- from Reineke's (1933) development of a stand density index to more recent uses to guide density control (Drew and Flewelling 1979; McCarter and Long 1986), and more recently as a component of growth and yield

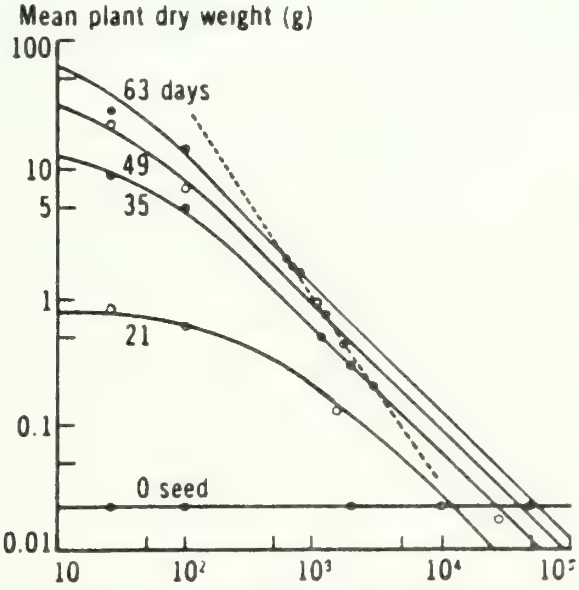

Figure 1. Reciprocal yield curves (solid lines) which describe the competition-density effect, and the -3/2 self-thinning line (dashed line). The reciprocal yield curves represent the maximum mean size possible for a given age and density. The -3/2 line limits the maximum mean size for a given density regardless of age (graph from Yoda et al, 1963).

models (Smith and Hann 1986; Lloyd and Harms 1986). Applications of competition-density theory to forest stands have been less common, and the results have generally been mixed (Ando 1968; Aiba 1975; Drew and Flewelling 1977; Peet and Christensen 1980). Forestry applications of the principles of competition-density theory and the self-thinning law usually use above ground stem volume in place of plant biomass and measure density as trees per unit area.

REVERSE-J CURVE

The reverse-J-curve describes the natural decline in number of trees (density) per unit area with age in stands where self-thinning is occurring (Figure 2a). This decline in number of individuals with age in dense populations is well recognized and is a general attribute of normal yield table data. The number of trees in the "normal" stand declines with age at a rapid rate initially, but the rate is much slower in the later stages of stand development when trees are larger. Stands which are initially at low densities generally do not decline rapidly in density and have a shallow reverse-J-curve. Stands with high initial density decline in density very rapidly and have a steep reverse-J-curve.

The reverse-J curve becomes more linear (Figure 2b), but still maintains the reverse-J shape when viewed on axes representing age in linear form and number of trees transformed logarithmically.

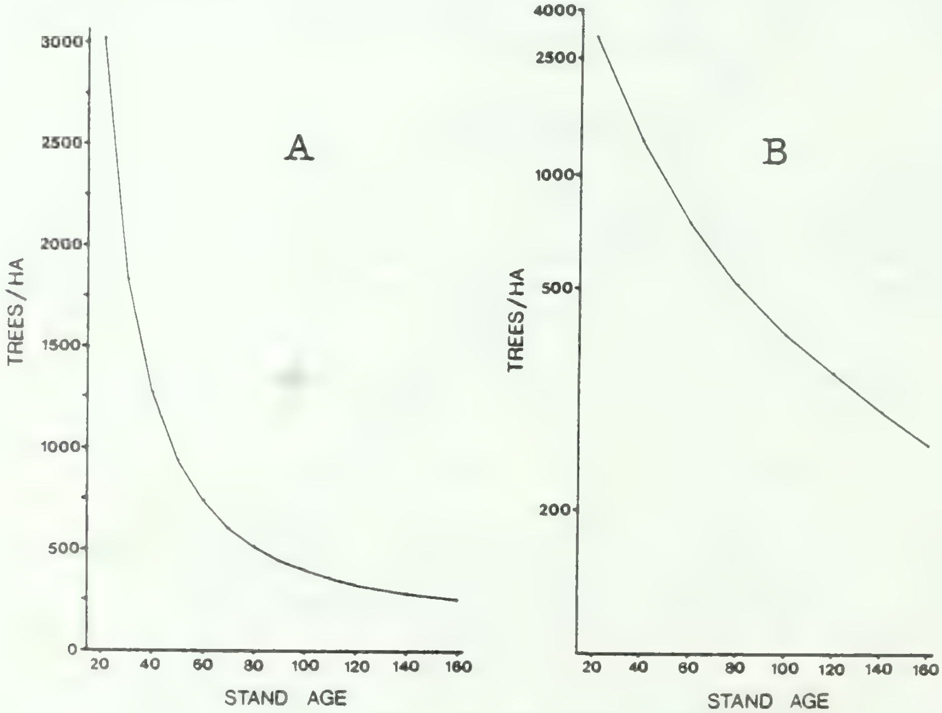

Figure 2. Reverse-J decline in density with age curve for Douglas-fir. Figure 2a shows the decline in density on linear coordinates while Figure 2b shows the same data with a logarithmic transformation of the trees/ha axis (data from McArdle et al. 1961).

CORRELATED CURVE TREND

The correlated curve trend was first observed by O'Connor (1935) in spacing trial data for Pinus elliottii (Engelm.) in South Africa. The correlated curve trend describes the relation of mean tree volume (or mean diameter), number of trees per unit area, and stand age as a branched sigmoid curve (Figure 3). Each branch of the curve represents a stand of a different initial density (trees per unit area). Trees in stands with high initial densities reach their maximum mean size (either volume or diameter) earlier than trees in stands with lower initial densities; however, the maximum mean tree size in a stand of lower initial density is greater than in stands with higher initial densities.

THREE-DIMENSIONAL MODEL

Each of the three relationships described above involves two of the variables: mean size, density and age. The relationships described by the competition-density effect (Figure 1) and correlated curve trend (Figure 3) also vary with the third variable: stand age and initial density, respectively. The three variables used in these three relationships -- stand age, density and mean tree volume -- can be combined into a three-dimensional graphical model. Each of the three aspects of the the three dimensional model presents one of the two-variable models discussed above. This three-dimensional model represents the change in mean tree volume over time for stands of different initial densities for a specific site quality (Figure 4). Although several researchers have combined the three variables (mean size, density, and age) into a single two-dimensional graph (Tadaki 1963; Ando 1968), the first known use of the three variables in a three-

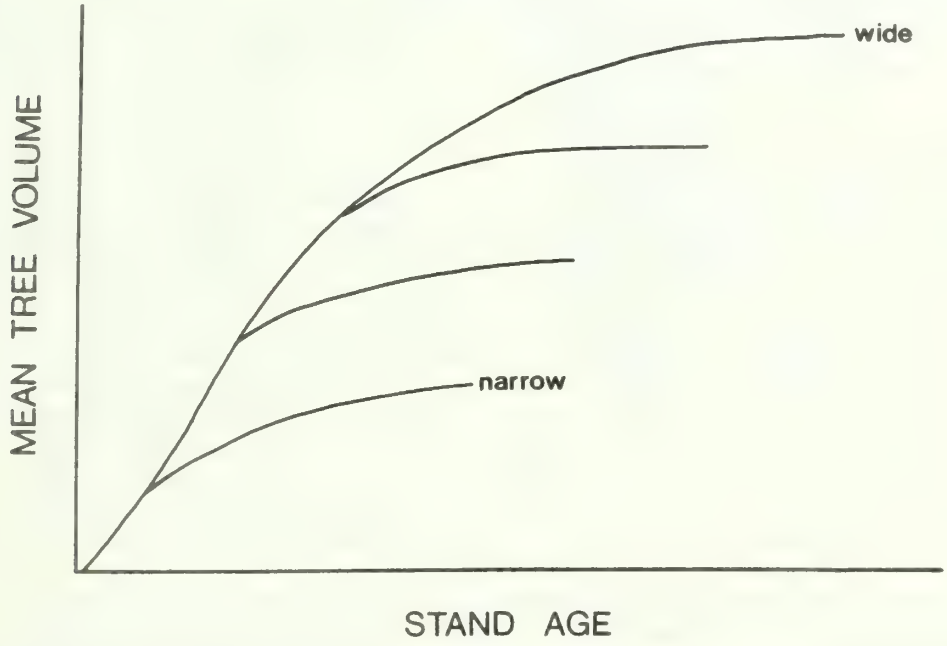

Figure 3. Schematic version of the correlated curve trend showing increase in mean tree volume with age of stands of different initial spacing. The widely spaced stand reaches a much larger mean tree volume than the narrower spaced stands.

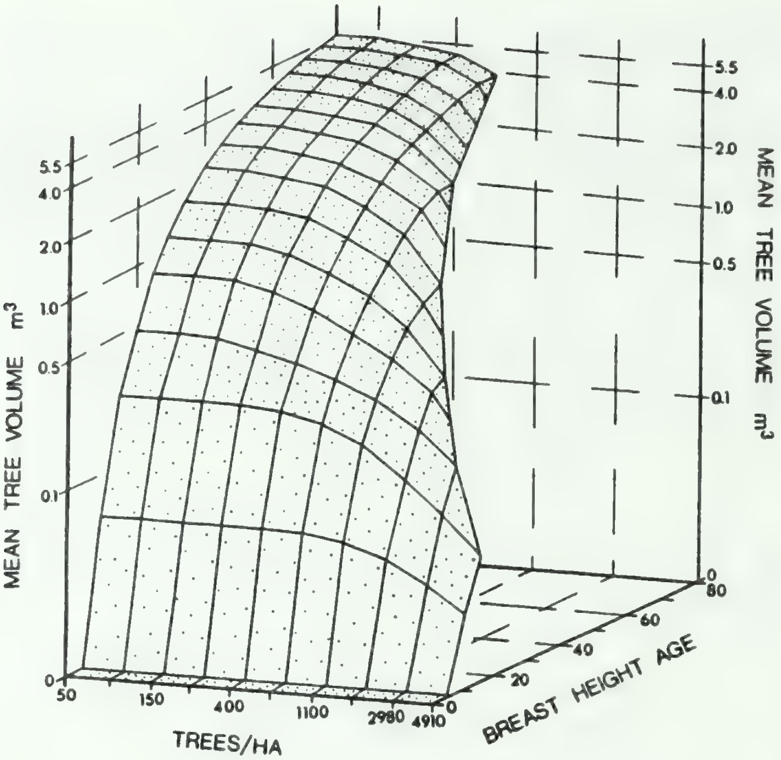

Figure 4. Three-dimensional model relating stand density (trees/ha), breast height age, and mean tree volume based on TASS growth model estimates for site index 44 meters (50 year).

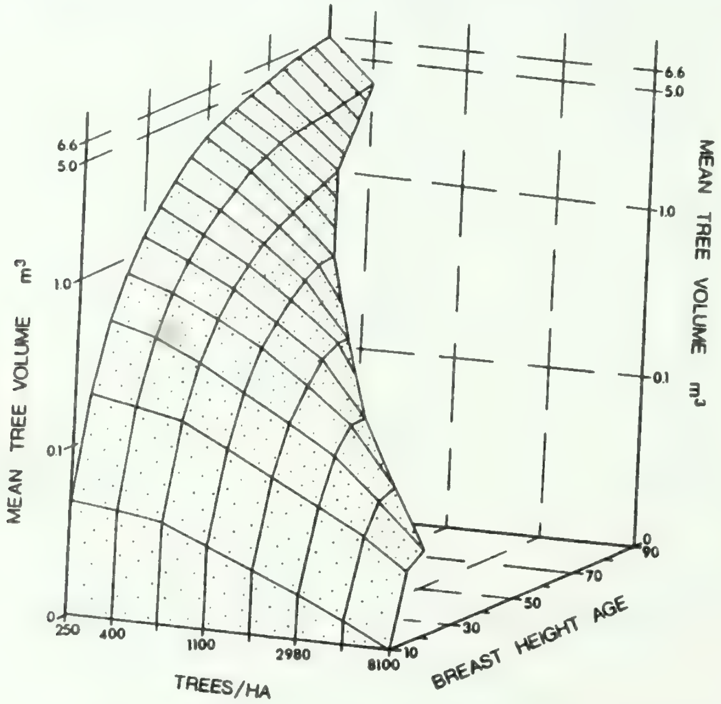

Figure 5. Three-dimensional model relating stand density (trees/ha), breast height age, and mean tree volume based on DFSIM growth model estimates for site index 44 meters (50 year).

dimensional graphical format (Figure 4) was by Sato (1983) who used stand volume instead of mean tree volume. Similar three-dimensional expressions were presented by Chang (1984), but without inclusion of the principles of competition-density theory, the reverse-J curve, or the correlated curve trend, and more recently by Lloyd and Harms (1986).

METHODS

The three-dimensional surface presented in Figure 4 was developed from Douglas-fir growth and yield estimates produced with the TASS model (Tree and Stand Simulator, Mitchell and Cameron 1985). A similar surface (Figure 5) was constructed from estimates from the DFSIM (Douglas-fir Stand Simulator, Curtis et al. 1981). Both surfaces were constructed using a three-dimensional graphics software package (Surface II, Sampson 1978) that interpolates between non-uniform, spatially distributed data points to construct a grid matrix.

Data sets from the two growth and yield models were generated with simulation runs for stands of various initial densities for site index 44 meters (Site Class I; 50 year). Breast height age was used as the age variable and was assumed to be six years less than total age. Density and mean tree volume were transformed with natural logarithmic transformations before the grid matrices were constructed. Density values from the grid matrices were rounded to the nearest whole multiple of 10 after an inverse-logarithmic transformation from the log-density values used in the generation of the grid matrix (e.g., log 6 = 403.4 ~ 400 trees/ha).

The grid matrices consisted of equally spaced grid nodes at a specific age and density which were established by interpolating from the nearest age and density data. An algorithm which weighted nearby data points using an inverse distance to the 6th power function was used to calculate the mean tree volumes at each grid node.

DISCUSSION

The three-dimensional model provides a visual representation of the increase in mean tree volume at different spacings over time and facilitates comparisons of different growth and yield models for a specific site quality over their common range of ages and densities. It could also serve as a baseline model from which to compare other growth projections as well as the growth of actual stands. For example, the three-dimensional surface constructed from growth and yield data represents the potential growth of unthinned stands for a range of spacings. Comparisons of this surface to actual stand data would provide valuable information not only to verify or calibrate the growth and yield model, but also to be used as a control or baseline for observed plot data.

Without the three-dimensional model comparing growth and yield models with actual data would require simulating stands from some initial density. Different growth and mortality functions within the models would probably create two distinctly different stands. Comparing the models with an actual stand (whose origin or initial density is unknown) at an intermediate stand condition may involve trial and error to get the growth and yield models to the desired intermediate age and density. The three-dimensional model avoids this difficulty by interpolating between growth and yield predictions to provide volumes at any desired density/age combination.

Stand volume may also be used on the vertical axis in place of mean tree volume to permit comparison of growth and yield models on a stand volume basis. The three-dimensional surface may be further standardized by replacement of the age axis with dominant tree height. Dominant height -- because of its independence from the effects of density and sensitivity to site quality -- may serve as a useful measure of biological time and permit the three-dimensional surface to apply to more than a single site quality. This principle has permitted the standardization of a single yield table over a range of site qualities (Assmann 1970; Mitchell and Cameron 1985), and dominant height has been used as a measure of biological time in some competition-density diagrams (Tadaki 1963; Ando 1968).

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AN EVALUATION AND COMPARISON OF TWO DISTANCE-INDEPENDENT FOREST PROJECTION MODELS IN THE INLAND NORTHWEST

Donald A. Patterson and Charles T. Stiff[1]

ABSTRACT. The northern Idaho versions of the Stand Prognosis Model and the Stand Projection System (SPS) were evaluated and compared using plot data from 45 managed, even-aged Douglas-fir stands distributed throughout the Inland Northwestern United States. Tree list input for model projections were derived by backdating tree and stand attributes. The average projection length was 12 years, ranging from 8 to 20 years. Predicted mean ft^3 volume growth per acre for Prognosis without calibration and SPS were 79% and 110% of mean observed volume growth, respectively. SPS bias was related to overprediction of diameter growth, while Prognosis underprediction was related mostly to the level and distribution of predicted mortality. Prognosis with calibration predicted volume growth to be 54% of the mean observed volume growth.

INTRODUCTION

For more than a decade, forest managers in the Inland Northwest have relied upon Stand Prognosis Model (Wykoff et al., 1982) projections for scheduling harvests, updating inventories, and comparing alternative stand treatments. The recent release of the Stand Projection System (Arney, 1985) has provided managers a choice and a dilemma. The Stand Prognosis Model (Prognosis) and Stand Projection System (SPS) are both individual tree distance-independent stand projection models providing future total volumes across a wide variety of species types, site conditions, and stand structures. However, the models differ in growth projection strategies and performance.

The Inland Northwest Growth and Yield Cooperative (INGYC), located at the University of Montana, has funded several research projects to evaluate Prognosis and SPS performance using permanent plot data. Unlike previous studies, this paper compares both models using backdated tree and stand data from managed, even-aged Douglas-fir stands. Our analyses are intended to provide performance information to help potential users assess model reliability under a variety of forest conditions, and to help developers improve subsequent models.

MODEL DESCRIPTIONS

Stand Prognosis Model. All facets of predicted tree development in version 5.1 of Prognosis (Wykoff, 1986) are dependent in part on dbh or dbh increment. Species-specific 10-year basal area increment for large

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trees (dbh equal to or greater than 3 inches) is predicted from initial dbh, ratio of live crown length to total height, stand density (CCF = crown competition factor), stand site quality (% slope, elevation, aspect, habitat type and geographic location), and relative tree size (BAL = basal area per acre in larger trees). Large tree (dbh > 10 inches) height increment is predicted by species from initial dbh and height, dbh increment, and habitat type. For trees less than 3 inches dbh, tree growth is predicted by height increment from initial height, CCF, BAL, and stand site quality. A weighted height increment based on small and large tree models is used if dbh is between 3 and 10 inches. Mortality predictions are dependent on species, dbh, relative diameter (dbh/mean stand dbh), dbh increment, estimated potential dbh increment, stand basal area per acre, and habitat type. Two additional mortality components reflect approach to normality and maximum stand basal area.

Prognosis component models were calibrated using National Forest inventory data from northern Idaho, eastern Washington, and western Montana that represent both unmanaged and managed stands. The models are based on initial tree dimensions and site attributes, which avoid limitations associated with stand age and site index. Optional calibration procedures use samples of current increment to localize projections for variations in site not represented in model parameters. Random effects on growth and mortality components represented in the model can be altered or suppressed by users.

Stand Projection System. SPS predicts top height (the average height of the largest 40 trees per acre by dbh) increment from site index and age. Growth periods are defined as equal increments of top height through time. Top height increment is allocated to trees within the stand on the basis of relative tree size (total height/stand top height) and CCF. Subsequently, dbh growth is predicted from initial dbh and stand top height, top height increment, and CCF. Potential and modifier functions are used for both dbh and height growth. Tree mortality is dependent on the initial number of trees per acre and CCF, and is distributed to trees by diameter class using a "decay" function.

SPS was developed using permanent plot data from even-aged coastal Douglas-fir stands in Washington and Oregon. Adjustments were made in the increment models for inland Douglas-fir and other species in the Inland Northwest. Calibration procedures and random effects on growth and mortality components are not available.

METHODOLOGY

TEST DATA

Data for model evaluation and comparison were drawn from 45 managed, even-aged Douglas-fir stands established by the Intermountain Forest Tree Nutrition Cooperative (IFTNC). The stands are evenly distributed between six geographic regions (1 = northern Idaho; 2 = Montana; 3 = central Idaho; 4 = northeastern Oregon; 5 = central Washington; and 6 = northeastern Washington) in the Inland Northwest (Figure 1). Thirty-nine of the 45 stands have been thinned within the last 7 to 19 years, while 6 stands were not thinned. Although stands are located on a variety of habitat types, species composition is predominately Douglas-fir (Table 1). Each stand has 6 one-tenth acre square plots, four treated with nitrogen fertilizer (200 and 400 lbs per acre) and two

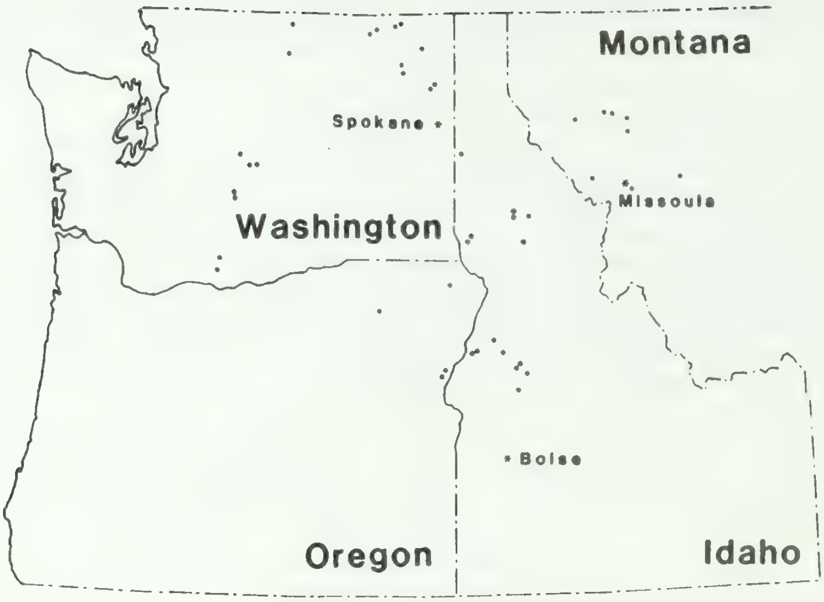

FIGURE 1. Geographic location of 45 IFTNC stands.

reserved as controls. Model projections used only data from the 90 control plots which were measured in 1985.

BACKDATING PROCEDURES

Tree list input for model projections were derived by backdating tree and stand attributes. Attributes were backdated by subtracting their observed or estimated change during the period from their 1985 values. For thinned stands, the backdate period was to the time of thinning from the fall of 1985 (an average of 12 years). For unthinned stands, the backdate period was 15 years. Three individual tree attributes (total height, dbh, and crown ratio) and stand density were backdated using the following procedures:

1. Total Height - Height growth for dominant trees was predicted by species based on observed stand age and site index. Douglas-fir was predicted with stand-specific equations developed from IFTNC stem analysis data. Published regional equations (Deitschman and Green, 1965; Barrett, 1978) were used for other species. The remaining trees within the stand were then allocated height growth based on the ratio of observed height to predicted dominant height. Backdated height was derived by subtracting height growth from observed height.

2. Dbh - Backdated dbh was calculated as observed dbh minus observed dbh increment. Dbh increment was cambial (measured from increment cores) plus bark (estimated using stand-specific bark thickness ratios) growth.

3. Crown Ratio - Initial crown ratio was calculated by dividing backdated crown length (observed crown length minus height growth) by backdated total height. Since most stands had been recently thinned, height to the base of the live crown was assumed to remain unchanged.

TABLE 1. Common names, scientific names and frequency of species on 90 IFTNC control plots.

Species	Scientific Name[a]	n	%
Western white pine	**Pinus monticola**	2	0.1
Engelmann spruce	**Picea engelmannii**	3	0.1
Western red cedar	**Thuja plicata**	3	0.1
Lodgepole pine	**Pinus contorta**	22	1.1
Western larch	**Larix occidentalis**	54	2.7
Grand fir	**Abies grandis**	62	3.1
Ponderosa pine	**Pinus ponderosa**	126	6.2
Douglas-fir	**Pseudotsuga menziesii**	1759	86.6
TOTAL		2031	100.0

[a] Hitchock and Cronquist, 1973

4. Stand Density - Pre-thinning stand densities were estimated by including 1-inch diameter class stump tallies at the beginning of projections. Stump tally trees were then removed by model thinning algorithms during the first projection cycle. Backdated stand densities were necessary to simulate thinning release and calibrate Prognosis projections.

STAND PROJECTIONS

Model projections using plot data from 45 backdated IFTNC stands began at the time of thinning (15 years prior to 1985 for unthinned stands) and ended with the 1985 measurements. The average projection length was 12 years, ranging from 8 to 20 years. A summary of post-thinning IFTNC stand attributes is given in Table 2. Stand site index was calculated as the average for 12 dominant trees per stand (2 trees per 1/10 acre plot) using Monserud's (1984) site index curves for inland Douglas-fir.

TABLE 2. Summary of post-thinning IFTNC stand attributes.

Stand attribute	Mean	Minimum	Maximum	Std dev
Site index (ft)	60.3	45.0	88.0	10.2
Volume (ft^3/ac)	3847.4	1202.0	8831.0	1366.1
Basal area (ft^2/ac)	140.7	72.0	271.0	36.4
Top height (ft)	78.2	45.0	116.0	13.8
Quadratic dbh (in)	11.3	7.3	17.6	2.2

Three types of projections were made using Prognosis: i) without dbh increment calibration but with mortality, ii) with dbh increment calibration and mortality, and iii) with dbh increment calibration but without mortality. Since SPS does not have growth calibration, only two types of projections were made: i) with mortality, and ii) without mortality. Prognosis equations were used to calculate stand volume, top height, and median dbh (diameter of the tree of median volume minimizes the effect of outliers) for observed data and all model projections. Comparisons without mortality used tree lists with trees lost to mortality added back prior to calculating stand statistics. For Prognosis, projections included random effects for stand-level residual analyses. Separate projections were made without random effects to evaluate individual tree predictions.

RESIDUAL ANALYSES

Bias, precision, and trends in Prognosis and SPS projections were evaluated and compared using residuals (observed minus predicted values) plotted against post-thinning stand attributes. The INGYC Residual Analysis Committee specified the following minimum standards:

1. Whole Stand - Residuals for total cubic-foot volume per acre, top height, and median dbh were plotted against median dbh, top height, stand density (basal area per acre/square root of median dbh), projection period length, and stand site index.

2. Individual Tree - Residuals for individual tree dbh and height were plotted against median dbh, top height, stand density, projection period length, and predicted dbh increment.

All residuals were similarly plotted by habitat type and IFTNC geographic region. Prediction bias in volume, top height, median dbh, and trees per acre (TPA) were also evaluated using mean residuals and percent of mean observed growth (PMOG). PMOG was calculated as the predicted growth (difference between mean observed growth and mean residual) divided by mean observed growth. For TPA calculations, PMOG was defined in terms of mean observed TPA instead of growth. The standard deviation for residuals was a measure of projection precision.

RESULTS AND DISCUSSION

Only stand-level comparisons of volume, top height, and median dbh growth are discussed in this paper. Emphasis is on volume growth, with top height and median dbh growth providing insight into which model components explain differences between observed and predicted volume growth. Our discussion of model performance is based on residuals plotted against site index. Only volume residuals for projections with mortality and excluding calibration are displayed. A summary of Prognosis and SPS residuals for all projections is given in Table 3.

Prognosis and SPS volume residuals plotted against site index (Figure 2) indicated both models had substantial bias in predicting volume growth. Predicted mean volume growth for Prognosis and SPS were 79% and 110% of mean observed volume growth, respectively. Prognosis and SPS also showed trends over site index, explained by corresponding trends in predicted top height and median dbh growth, respectively.

Median dbh residuals over site index indicated that both models overpredicted median dbh growth. Predicted median dbh growth for Prognosis and SPS were 141% and 138% of the mean observed median dbh growth, respectively. SPS residuals also showed increased overprediction with larger values of site index. Such a trend suggested an adjustment for site quality was needed in the model's height-dbh relationship.

Prognosis (without calibration) top height residuals over site index indicated predicted top height growth to be 80% of the mean observed top height growth. On the other hand, SPS overpredicted top height growth by only 1%.

CALIBRATION EFFECTS

All IFTNC trees had been sampled for 10-year radial increment which were used to calibrate Prognosis projections. Although calibration improved dbh growth predictions, it reduced Prognosis top height growth and increased estimated mortality. Therefore, calibration resulted in increased underprediction of volume growth. However, calibration removed trends in volume and top height growth over site index.

MORTALITY EFFECTS

Gross volume (total stand volume per acre) residuals indicate success and/or failure of a model's growth components in predicting observed volume growth. However, net volume (total stand volume per acre minus volume lost to mortality) residuals include effects from both a model's growth and mortality components. Together, gross and net volume residuals isolate the effect that predicted mortality has on volume growth prediction. Prognosis with calibration predicted gross and net volume growth to be 80% and 54% of the mean observed gross and net volume growth, respectively. Therefore, the growth components accounted for 20%, while the mortality component accounted for 26% of the underprediction in stand volume growth. Prognosis predicted 11% fewer trees per acre than was observed.

The underprediction in Prognosis volume growth can be partially explained by the amount and distribution of predicted mortality by dbh percentile class (Figure 3). Notice that 8% of the trees in the top 10 percentile class had died. Observed mortality in the top 10 percentile class was less than 1 percent. Higher predicted mortality in the larger dbh classes resulted in a large decrease in net volume growth.

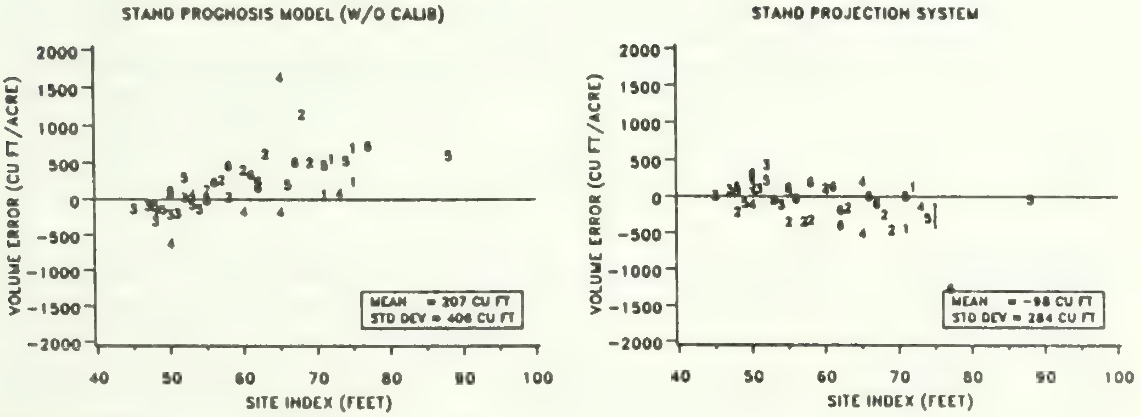

FIGURE 2. Differences between observed and predicted total ft^3 volume per acre for Prognosis and SPS projections with mortality and without dbh increment calibration. Plotted numbers correspond to IFTNC geographic regions.

TABLE 3. Summary of Prognosis and SPS residuals from 45 IFTNC stands.

		PROGNOSIS			SPS		
Variable	Projection[a]	Mean	Std Dev	PMOG[b]	Mean	Std Dev	PMOG
		ft^3/acre					
Volume	A	453	299	54%	--	--	--
	B	207	406	79%	- 98	284	110%
	C	201	200	80%	-172	360	118%
		ft					
Top Height	A	3.5	2.8	65%	--	--	--
	B	2.0	3.8	80%	-0.1	2.5	101%
	C	4.0	2.7	60%	-0.1	2.5	101%
		in					
Diameter[c]	A	-0.12	0.35	111%	--	--	--
	B	-0.46	0.50	141%	-0.42	0.58	138%
	C	0.14	0.33	87%	-0.36	0.54	132%
		trees/acre					
Trees	A	23	15	89%	--	--	--
	B	19	12	91%	9	14	96%

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[a] A = including calibration and mortality; B = excluding calibration and including mortality; and C = including calibration (Prognosis only) and excluding mortality.

[b] Percent of mean observed growth (PMOG) is the difference between mean observed growth and mean residual divided by mean observed growth.

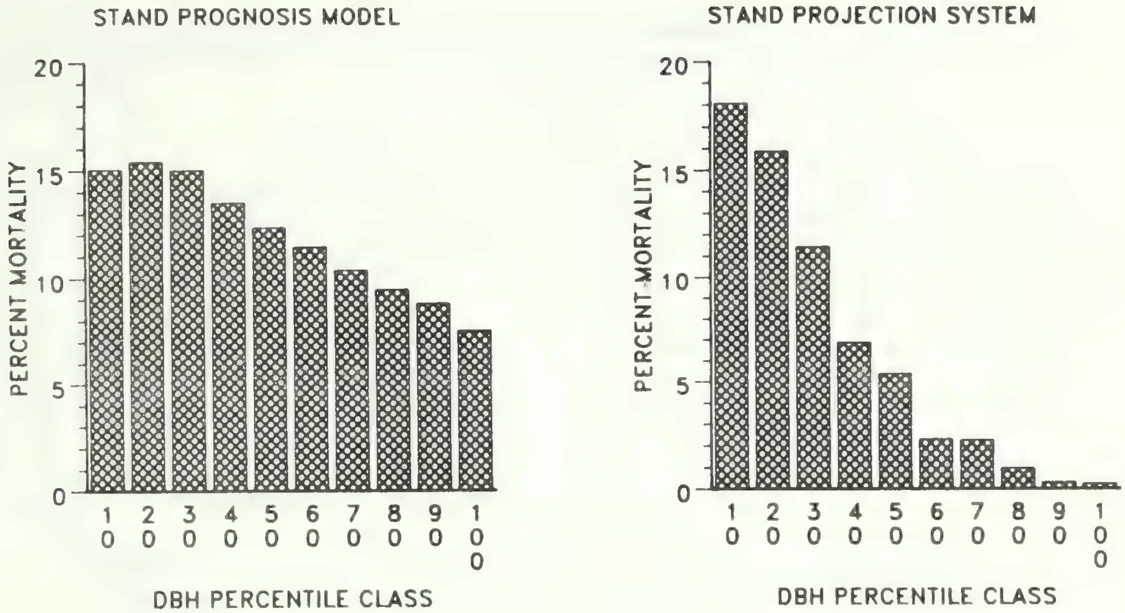
[c] Diameter of the tree of median volume.

SPS predicted gross and net volume growth to be 118% and 110% of the observed gross and net volume growth, respectively. The growth components accounted for an 18% overprediction, while mortality accounted for an 8% underprediction in stand volume growth. Since the mean top height residual was only -0.1 feet, overprediction in median dbh growth (132% of the mean observed median dbh growth) accounted for most of the overprediction of gross volume growth.

SPS distributed a greater percentage of mortality to smaller trees in the stand (Figure 3). In addition, SPS predicted only 4% fewer trees per acre than was observed.

CONCLUSION

Prognosis and SPS growth projections were compared using backdated tree and stand data from managed, even-aged Douglas-fir stands. Since 87% of the stands had been recently thinned, this study was primarily a validation of both models' ability to predict short-term thinning response. Considering our results, SPS performed better in projecting this type of stand. On the other hand, several INGYC validation studies using data from "unmanaged" stands have concluded that Prognosis was superior. Together, these results suggest that model performance for a given stand is related to the model's growth projection strategy. Prognosis, with component models based on initial tree dimensions and site attributes, is perhaps best suited for "unmanaged" stands where site index and stand age are either inappropriate or impossible to



STAND PROGNOSIS MODEL

STAND PROJECTION SYSTEM

FIGURE 3. Distribution of predicted Prognosis and SPS mortality.

determine correctly. SPS, which is based on top height increment, may be more suited to the managed, even-aged stands in the Inland Northwest.

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COMPARISON OF YIELD-FORECASTING TECHNIQUES USING LONG-TERM STAND HISTORIES

Albert R. Stage and David L. Renner[1]

ABSTRACT. What can be learned from comparison of long-term growth plots to a growth model? Growth histories for as long as 70 years on 102 permanent plots in the northern Rocky Mountains have been compared to predictions produced by the Prognosis Model for Stand Development, a single-tree, distance-independent growth model. In addition, alternative methods of yield forecasting--ranging from using a normal yield table with several "approach to normality" adjustments to using precompiled yield tables from the Prognosis Model--are compared to document the progressive changes in ability to forecast stand development. The comparisons include starting from bare ground as well as starting with attributes of existing stands. The overall bias and variance has been analyzed to estimate effects of thinning, plot size, length of projection, and geographic proximity. Effects of mortality and accretion submodels have been separated. Approximately 80 percent of variability in cubic volume is due to uncertainty in the mortality estimates.

INTRODUCTION

Histories of stand development are a scarce resource for growth modelers. They also are a scary resource because the stand histories may show how imperfect are our best efforts to forecast stand development. However, evaluation of a growth model is not these histories' only use. Here, we describe how variation in yield forecasting has changed with time and how variation changes depending on the spatial scale of the forecast. Each of these analyses has a role in the process described elsewhere in these proceedings (Newberry and Stage) of deciding whether a given model is adequate for use in a particular decisionmaking application. Forest planners, who have of necessity assumed that timber yield forecasts were sufficiently accurate to be treated as if deterministic, can use these results to see how seriously in error might be the deterministic assumption.

DESCRIPTION OF DATA

Intermountain Research Station is the fortunate heir to records from 102 plots, some of which go back as far as 1914. The average duration is 39 years. About half of these plots were thinned at time of establishment. Nine plots were in plantations of Pinus monticola. Most of the plots represent Abies grandis, Thuja plicata, and Tsuga heterophyla series in the vegetation classification system (Daubenmire and Daubenmire 1968). Although many of the plots were initially selected to study yield of Pinus monticola, the standard for classification required only

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15 percent white pine. Furthermore, some of the plots were located specifically to study yield of *Pseudotsuga menziesia* and *Larix occidentalis*.

Geographic distribution of the plots is represented by UTM coordinates. Two clusters of plots are in two of our experimental forests, another cluster is near Clarkia, Idaho, and there is an additional scattering of plots elsewhere. This distribution provided a good basis for analysis of spatial variation.

Plot sizes varied, depending on tree size at establishment, from 1/10 acre to 4 acres. On the average, geometric mean of the ratio of plot area to quadratic mean diameter was 0.0418, or about 1/4-acre plots in stands of 6-inch trees. Fortunately, there was sufficient variation in the relative plot sizes to estimate spatial variation at plot level in addition to the between-plot analysis based on UTM coordinates.

RANDOMIZATION

In a strict sense, bias in these or any models cannot be estimated unless plots are located by a random process operating on a defined population. Because this process was not followed--or even appreciated in the early years of forestry research in North America--we must qualify the inferences that can be drawn from these data.

Reviews of establishment reports and plot histories reveal the following: in thinning comparisons, plot boundaries were shifted to encompass particular stocking levels; some plots, designated for studying yield of uncut stands, were located to represent a range of stocking; measurements of some plots have been terminated because of "excessive mortality"--usually caused by *Cronartium ribicola* or pole-blight of western white pine. Offsetting the biases caused by this lack of randomization at time of establishment is the superposition of a long series of random climatic events and pest impacts.

PLOT MEASUREMENTS

On most plots, all trees larger than 1-inch diameter at breast height (dbh) were tagged at establishment. A few plots with a distinctly smaller *Thuja* understory omitted *Thuja* less than 3 inches dbh from the initial tally. The analyses reported here are based only on trees *present* and tagged at time of establishment. Ingrowth was omitted because we had made no provision for invoking the Regeneration Establishment Model (Ferguson and Crookston 1984) when these analyses were planned.

Diameters were measured with a tape and recorded to nearest 0.1 inch. Heights of 15 to 20 trees of each species were initially measured from a fixed location with a transit. Later measurements used Abney levels or various clinometers read to nearest degree of angle.

Simulations by the Prognosis Model relied on default estimates of crown ratio provided by the model. To improve the initialization of crown ratios in thinned stands, additional tree records representing trees removed were added to the initial inventory and then removed by the "prescription thinning" option of the model.

Two plots had been thinned more than once. Statistics for these plots were computed by adding the estimated intermediate yields (which included estimation errors up to time of thinning) to the final estimated plot volumes, and the simulation restarted with just those trees left after thinning. For comparison, actual intermediate yields were added to the final plot volumes.

MODELS EVALUATED

We evaluated three models representing a historical sequence of yield forecasting techniques for the northern Rocky Mountains. These include Haig's (1932) normal tables, Watt's (1960) modification of these tables allowing for "approach-to-normality," and the Prognosis Model for Stand Development, version 5.1 (Stage 1973; Wykoff et al. 1982; Wykoff 1986). Estimates based on the Prognosis Model include the Regeneration Establishment Model (Ferguson and Crookston 1984; Ferguson et al. 1986) when the projections start from "bare ground."

Watt's (1960) estimates of approach-to-normality were based on analyses of these same plots using data through about 1952. Later analyses of mortality history of a subsample of trees and measurement periods by Hamilton (1986) form a portion of the mortality functions in the Prognosis Model.

ANALYSIS

Model-based estimates have been compared to actual stand development to meet the requirements for validating growth models specified by Newberry and Stage elsewhere in these proceedings.

BIAS AND PRECISION (PROGNOSIS V. 5.1)

Means and standard deviations of observed minus predicted values were calculated for predictions starting with time of plot establishment and ending at last measurement--an average of 38.9 years. Two sets of simulations include one that represents the behavior of the full model and another that represents all sources of variation except mortality. In the latter set, each tree that died was removed from the simulation at the start of the 10-year cycle during which it died. Hence, this latter set represents analysis of a data set completely independent of data used to calibrate the models. The set including mortality errors is partially compromised because parts of these plot data have been used in model calibration.

Table 1 contains estimates of bias and precision for four stand attributes. Regression of these residuals on starting height, relative density, and site index resulted in no regression coefficients significantly different from zero at the 95 percent confidence level.

TABLE 1. Differences between observed and predicted stand development for 102 plots. Average prediction length is 38.9 years.

Attribute	Omitting mortality errors		Including all errors	
	Mean	Std. dev.	Mean	Std. dev.
Volume (cu.ft.)	+80.2	±1177	-1166	±2509
Top height (ft.)	-0.4	±10.2	-3.0	±12.4
Basal area (sq.ft.)	+0.6	±20.6	-32.6	±56.3
Diameter				
Quadratic mean	+0.10	±0.7	+0.20	±1.2
10 percentile	+0.01	±0.7	+0.04	±1.2
50 "	+0.28	±1.3	+0.29	±1.4
90 "	+0.37	±2.8	+0.54	±3.2

COMPARISONS WITH PRIOR TECHNOLOGY

Management applications for which yield or present net worth per se is the appropriate decision variable may require comparison with prior yield estimation procedures (Newberry and Stage, elsewhere these proceedings). For northern Rocky Mountain types represented by our data, the previously documented yield estimation techniques were, first, Haig's (1932) normal yield tables and, later, Watt's (1960) estimates of approach-to-normality applicable to existing stands. In this section, we compare the older methods to the Prognosis Model for both "bare ground" estimates when no data are available to describe the stand other than site index and age, and for the case where a detailed stand inventory is available.

For the bare ground case, site index would be available only from a previous stand, or from some estimation techniques based on climate, soils, or habitat type. For these plots, the only estimate of site index that was available was derived from the same stand that supplied the actual yield estimate. This "realized" site index represents the sum of the site factors plus effects of accidents of climate and rates of initial stand establishment. Therefore, we modified the observed site index to introduce the variation we would expect between site index determined without reference to existing stand and that observed on our existing stands. To do this, we added a normal random deviate with a mean of zero and a standard deviation of ±6 feet. Estimates produced by the several models are compared for natural stands (Table 2), for white pine plantations starting from bare ground (Table 3), and for existing natural stands (Table 4).

TABLE 2. Yield forecasting errors for 93 even-aged stands at an average age of 104 years, using only site characteristics and stand age.

Source of estimate	Average difference (obs.-pred.)	Standard deviation	Root mean square error
	- - - - - - (cubic feet) - - - - - -		
Haig (1932)	-3767	±3408	±5080
Using Prognosis with Regeneration Establishment Model (1986) to estimate initial stand characteristics	529	±4065[a]	±4099

[a] Includes some random variation built into simulation model.

TABLE 3. Yield forecasting errors for nine plantations, at an average age of 52 years, using only site characteristics and stand age.

Source of estimate	Average difference (obs.-pred.)	Standard deviation	Root mean square error
	- - - - - (cubic feet) - - - - - -		
Haig (1932)	-987	±847	±1301
Using Prognosis with Regeneration Establishment Model (1986) to estimate initial stand characteristics	951	±1327[a]	±1633

[a] Includes some random variation built into simulation model.

TABLE 4. Yield forecasting errors for 93 naturally regenerated stands, after an average of 40 years growth, using initial stand, site, and treatment characteristics. Mean net increment equals 2,600 cubic feet.

Source of estimate	Average difference (obs.-pred.)	Standard deviation	Root mean square error
	- - - - - - (cubic feet) - - - - - -		
Haig (1932) (constant normality)	-1118	±3544	±3716
Watt (1960) (cu. ft. approach to normality)	-1340	±3571	±3814
Prognosis version 5.1 (no ring data)	-1216	±2595	±2866

Whereas Tables 2 and 3 indicate that improvements in yield estimates for bare ground have come mainly from reduced bias, but at the expense of somewhat increased standard deviations, Table 4 shows that bias for existing stands has changed little and that the improvement is in increased precision.

SPATIAL VARIATION

Foregoing analyses show that there is a great deal of variation in yield at the sample plot level. However, before this information on variation can be relevant to management decision analysis, it must be scaled for the difference between the sizes of the research plots and the sizes of the stands to which the models will be applied. The following analysis is a first approach to estimating variances to be expected at the stand level. The analysis is a sequence of five steps:

1. Fit a linear regression model to the residuals (observed minus predicted values of cubic foot volume). Pass the residuals from this bias model to the next step.

2. Fit a log-linear regression model to the squares of residuals from step 1. Variables in this regression are logarithm of projection length (L) and logarithm of plot area divided by quadratic mean dbh (A/QMD).

$$\ln(DEV^2) = 7.313 + 1.4514 \ln(L) - 0.4859 \ln(A/QMD) \qquad (1)$$

3. Calculate a normalized residual for each plot by subtracting the bias estimated from step 1 and dividing by DEV estimated in step 2.

4. Calculate geographic distances between all possible pairs of plots and sort plot-pairs into groups based on their separation.

5. Within the separation groups, calculate the covariance and correlation between normalized residuals for each pair of plots.

The spatial autocorrelations for the groups are listed in Table 5. Plotted on semilog scales, these data (excepting last point) form a straight line passing through correlation = 1 at a separation of 10 meters.

TABLE 5. Spatial autocorrelation of residuals of total cubic foot volume estimates, including all sources of variation.

Separation (meters)	Number of pairs	Mean separation (meters)	Correlation
11 - 100	66	70	0.675
101 - 1,000	275	365	0.447
1,001 - 10,000	559	3,605	0.069
10,001 - 100,000	2,387	64,815	-0.056
100,000 - 1,000,000	1,864	156,418	-0.051

VARIANCE OF STAND ESTIMATES

Using the results of the analyses reported here, we can estimate the variability of a yield forecast for an entire stand. We need to specify the plot size, spacing, and length of projection.

Consider a 30-acre stand divided into 30 plots of 1 acre each. A 35-year projection is to be evaluated at the end of which the stand will be 20 inches in mean dbh. Inserting these values in equation 1 provides an estimate of the standard deviation of projected volume of ±1,058 cubic feet for a single plot.

The next step is to calculate the variance of the mean of the projected values, allowing for the spatial correlation between plots. The variance of the mean is given by:

$$\text{Var} = \frac{\text{Var. per plot}}{n^2} \left(n + 2\sum_{i>j} r_{ij}\right) \tag{2}$$

where n = number of plots

r_{ij} = correlation between plots i and j estimated by interpolation in Table 5.

For our example, r_{ij} varies from 0.71 for pairs of adjacent plots whose centers are separated by 209 feet to 0.44 for the pair of plots at opposite corners of the 5 x 5 array of plots separated by 1,181 feet. For this example, twice the sum of the spatial correlations is 171.84. Hence, the variance multiplier in the brackets of equation 2, which would be 25 for independent samples, becomes 25 + 171.84 = 196.84 or about a fourfold increase in variance. Solving equation 2 for this example gives an estimate of ±812 cubic feet for the standard error of a yield forecast for the stand.

SUMMARY

Statistics describing the accuracy of growth forecasts for 102 plots in the grand fir-cedar-hemlock ecosystem show that most of the variability is attributable to mortality. Bias increases with length of projection at about 30 cubic feet per year. Bias was not significantly correlated with relative stand density, starting height, starting diameter, nor site index.

Variance of the estimates increased with length of projection and decreased with increasing plot size divided by quadratic mean diameter of the trees.

Correlation of plot errors between pairs of plots decreased linearly with the logarithm of their separation. At one-half mile separation, the spatial correlation was 0.31.

Information provided in this report can be used to evaluate the adequacy of the model for specific decisions. It also provides information on variability required if stochastic optimization procedures are to replace deterministic optimizing linear programming procedures such as FORPLAN.

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CONSEQUENCES OF VARIOUS GROWTH MODELS

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ABSTRACT. This paper focuses on assumed functions for the basal area or radial growth of individual trees. The integration of individual trees into a stand is accomplished by placing distributional assumptions on the parameters of the assumed growth function. The construction of the diameter distribution at an arbitrary time is then illustrated. This is followed by the construction of the transition probability matrix i.e. the probabilities of passing from diameter class i at time t to class j at time t + δ. In both cases uniform distributions are assumed for the parameters, but it is pointed out that the results for any assumed distribution can be accurately approximated by an appropriately weighted mixture of uniform distributions. Ideas for the incorporation of other factors, e.g. mortality, are presented. It is conjectured that the derivation of "observables" (diameter distributions, transition probabilities) for a range of such models should give insight into the feasibility certain models when given actual data.

INTRODUCTION

There are a multitude of functions that could be considered for representing basal area growth over time of individual trees. Prompted by Federer and Hornbeck (1987) we here explore the use of the so-called Weibull function. Specifically we show how the stand diameter distributions and transition probability matrices may be developed after placing distributional assumptions on the parameters of the growth function. A parallel approach can be employed for any assumed growth function.

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STAND DIAMETER DISTRIBUTIONS

Suppose that the basal area of a tree at time t can be expressed as the so-called Weibull function[1]

$$B(t) = B_f[1 - \exp\{-(t/\alpha)^\beta\}].$$

The trees that make up a stand, which for the time being may be supposed to be even-aged, do not, of course, have identical basal areas. To reflect this let the parameters of the above function be random variables that follow some prescribed distribution.

As a simple illustration suppose that B_f is a constant and that α and β are idependent random variables with distribution functions F_α and F_β respectively. It is reasonable to suppose that these variables have finite range, (L_α,U_α) and (L_β,U_β) say. Perhaps the simplest assumption that can be made is that α and β are uniformly distributed over their respective ranges.

Consider then what the radial (or diameter) distribution in the stand would be at time t, i.e

$$P\{R(t) \le R\} = P\{R_f\sqrt{1 - \exp[-(t/\alpha)^\beta]} \le R\}$$

$$= P\{\beta \ln(t/\alpha) \le f_r\}$$

where

$$f_r = \ln(-\ln(1-r^2)),\ r = R/R_f.$$

Note, in passing, that as $r^2 \to 0,\ f_r \to -\infty$,
$r^2 \to 1,\ f_r \to \infty$,
and if $r = \sqrt{1 - 1/e}$, then $f_r = 0$; accordingly
$r > \sqrt{1 - 1/e} = 0.79506 \Rightarrow f_r > 0$ and
$r < 0.79506 \Rightarrow f_r < 0$.

Now if $t < L_\alpha$ then $\ln(t/\alpha) < 0$ whence, if $f_r > 0$, i.e. if $R > 0.79596R_f$, then $P\{R(t) \le R_f\} = 1.0$ and one need be concerned only with $R < 0.79506R_f$. Conversely, if $t > U_\alpha$, then $\ln(t/\alpha) > 0$ and if $f_r < 0$, i.e. if $R < 0.79506R_f$, then $P\{R(t) \le R_f\} = 0$ so that one need be concerned only with $R > 0.79506R_f$.

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[1] The Weibull distribution arises as the asymptotic distribution of the first order statistic in a sample from a population with a finite lower bound and was named in honor of W. Weibull who pioneered its use in studies of the strength of materials (Weibull, 1939). Its use as a growth function arises from the fact that any continuous distribution function, rescaled has the properties of a growth function, namely monotonically increasing to a finite upper bound. To describe it as a Weibull function in this context can be regarded as a misnomer.

The situation where $L_\alpha < t < U_\alpha$ is, of course, slightly more complex.

Suppose $t < L_\alpha$ and let α, β be distributed uniformly over their respective ranges. Their joint density can be written $(1/R_\alpha R_\beta)d\alpha d\beta$ where $R_\alpha = U_\alpha - L_\alpha$ and $R_\beta = U_\beta - L_\beta$. The range of the joint distribution is, thus, a rectangular region and the probability that $R(t) < R$ is, in effect, the area of that part of the region in which $\beta\ln(t/\alpha) < f_r$. This is, perhaps, best illustrated by an example.

Let $(L_\alpha,U_\alpha) = (60,80)$ and $(L_\beta,U_b) = (1,3)$, $t = 50$ and $r =0.6$. Thus $f_r = \ln(-\ln(1 - .36)) = -0.8068$.

Consider the boundary $\beta\ln(50/\alpha) = -0.8068$. If $\beta = 3$ then $\alpha = 50e^{0.8068/3} = 65.43$, but if $\beta = 1$ then $\alpha = 50e^{0.8068} = 112.04 > 80$.

However, if $\alpha = 80$ then $\beta = -0.8068/\ln(50/80) = 2.3978$. We thus require the area of the shaded region in Fig. 1.

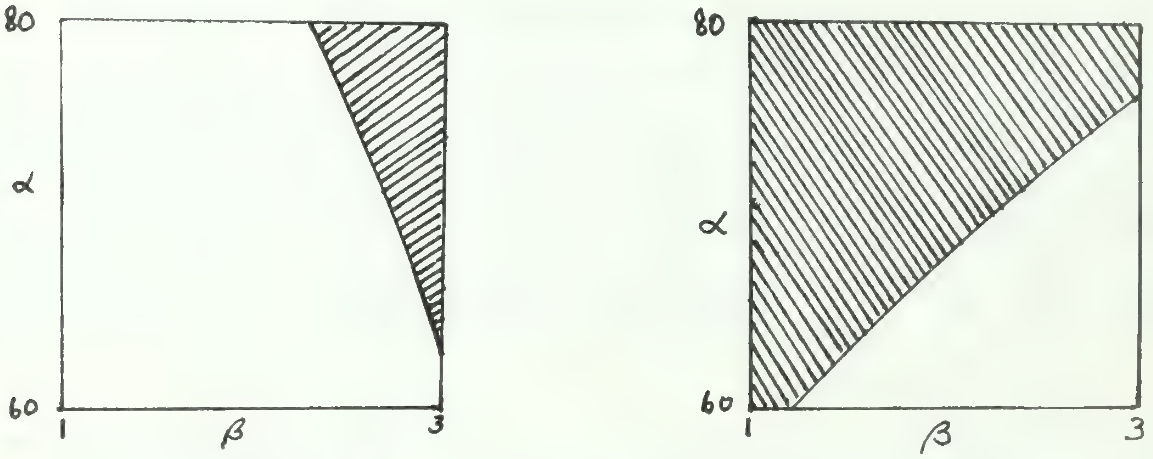

Figure 1. Figure 2.

The areas of itegration for the first and second examples.

Since $R_\alpha R_\beta = 40$, $P(R(50) \le 0.6R_f)$

$$= (1/40)\int_{65.43}^{80}\int_{f_r/\ln(50/\alpha)}^{3} d\beta d\alpha$$

$$= (1/40)[3 \times 14.57 - (-0.8068)50\int_{1.3086}^{1.6} 1/(\ln(1/x))dx].$$

Now $\int 1/(\ln(1/x))dx = -[\ln(\ln(x)) + \sum_{i=1}^{\infty} \ln^i(x)/i.i!]$ which, provided $x > 1$, is rapidly convergent for all practical values of x.

Accordingly $P\{R(50) \le 0.6R_f\}$

$$= \{3 \times 14.57 - (-0.8068)50(-[-.2235 - (-1.0252)])\}/40 = 0.2844.$$

Thus, if $R_f = 20$, $P(R(50) \le 12) = 28.44\%$.

In this way the radial distributions have been determined for $t = 10, 30, 50$ (Tables 1 and 2).

Next let $t = 90$ ($> U_\alpha$) and $r = 0.9$. Thus $f_r = 0.5073 > 0$. When $\beta = 3$, $\alpha = 90e^{-0.5073/3} = 76.00$ and when $\alpha = 60$, $\beta = 0.5073/\ln(90/60) = 1.2511$. The required area is indicated in Fig 2. It, however, appears to be somewhat more convenient to compute the complement of this area, namely

$$P\{R(90) \le 0.9R_f\} = 1 - (1/40)\int_{60}^{76.00}\int_{f_r/\ln(90/\alpha)}^{3} d\beta d\alpha.$$

Since the limits of integration for α, divided by t (=90), are now < 1, we cannot use the same series as in the case $t < L_\alpha$. However the above can be written

$$1 - (1/40)[3 \times 16.00 - 0.5073 \times 90\int_{1.1842}^{1.5} 1/(x^2\ln(x))dx]$$

$$(\text{Note } 90/60 = 1.5,\ 90/76.00 = 1.1842)$$

and

$$\int 1/(x^2\ln(x))dx = \ln(\ln(x)) + \sum_{i=1}^{\infty}(-1)^i\ln^i(x)/i.i!$$

whence

$$P\{R(90) \le 0.9R_f\} = 0.5636 \quad \text{or} \quad P\{R(90) \le 18\} = 56.36\%.$$

In this way the radial distribution for $t = 90$ has been obtained (Tables 1 and 2).

In the case of $L_\alpha < t < U_\alpha$ ($t = 70$, Tables 1 and 2) it is likewise a matter of determining the appropriate region of the rectangle and utilizing one or the other (or both) of the above series as the situation demands.

Suppose some other distributional assumptions are made concerning α and β while maintaining the finite ranges (L_α, U_α) and (L_β, U_β). The problem then becomes that of integrating a more complex function over the same regions. For many distributional assumptions there will not be a closed form solution; However, any distribution can be approximated by a mixture of uniform distributions and, with sufficient effort, the approximation can be made as accurate as desired. Accordingly the results for any distributional assumptions on α and β can be obtained as a weighted sum of the results for a set of uniform distributions over various ranges. Such procedure is, of course, computationally intensive but may be readily programmed. The same approach can be applied to any distributional assumption on R_f once the results for the assumed distributions of α and β, given R_f, have been obtained. The independence of R_f, α and β is assumed; the situation, otherwise, becomes highly complex.

TRANSITION PROBABILITIES

We now explore, under this model, the development of a transition probability matrix, i.e. the probability that a tree in radius (diameter) class i at time t will be in radius (diameter) class j at time t + δ. This may be achieved as follows. Let r = i/R_f, as before, and r_1 = (i+1)/R_f. Within the rectangle defined by (L_α,U_α) and (L_β,U_β) consider the region between the lines defined by $\beta \ln(t/\alpha) = f_r$ and $\beta \ln(t/\alpha) = f_{r_1}$.

Trees with combinations of α and β corresponding to points in this region will have radii between i and i+1 at time t. By considering the "corners" of this region we may determine the range of radii achieved by these combinations of α and β at time t + δ. This may cover several radius classes. Suppose that radius j is included. Let r_j = j/R_f and r_{j1} = (j+1)/R_f. Within the rectangle demarcate the region between the lines defined by $\beta \ln([t+\delta]/\alpha) = f_{r_j}$ and $\beta \ln([t+\delta]/\alpha) = f_{r_{j1}}$.

This region identifies the combinations of α and β that give rise to radii between j and j+1 at time t + δ. Integration over the intersection of these two regions thus gives the probability that a tree in radius class i at time t will be in radius class j at time t + δ. When α and β are uniformly distributed the probability is, in effect, the area of this intersection.

Table 1
Cumulative distribution function i.e. $P(R(t) \leq R)$ (%)

			t		
R	10	30	50	70	90
1	.97				
2	31.37				
3	52.45				
4	67.52				
5	79.33	1.34			
6	89.11	11.54			
7	97.43	28.23			
8	100	45.48			
9		60.87			
10		75.95	1.95		
11		88.91	11.36		
12		98.50	24.88		
13		100	53.87		
14			85.13	.14	
15			99.97	13.37	
16			100	54.09	
17				90.81	10.54
18				100	56.36
19					90.08
20					100

Table 2
Radial distribution by one inch classes (%)

	t				
Class	10	30	50	70	90
0 - 1	.97				
1 - 2	30.40				
2 - 3	21.08				
3 - 4	15.07				
4 - 5	11.81	1.34			
5 - 6	9.78	10.20			
6 - 7	8.32	16.69			
7 - 8	2.57	17.75			
8 - 9		15.39			
9 -10		14.58	1.95		
10 -11		13.46	9.41		
11 -12		9.59	13.52		
12 -13		1.50	28.99		
13 -14			31.36	.14	
14 -15			14.84	13.23	
15 -16			.03	40.72	
16 -17				36.72	10.54
17 -18				9.19	45.82
18 -19					33.67
19 -20					9.97

To illustrate let $t = 30$, $i = 9$, $\delta = 10$ with α, β and R_f as before. Then $r = 0.45$, $f_r = -1.4860$ and $r_1 = 0.5$, $f_{r_1} = -1.2459$. The line $\beta \ln(30/\alpha) = -1.4860$ passes through the points $(\alpha,\beta) = (80, 1.5151)$ and $(60, 2.1434)$ and the line $\beta \ln(30/\alpha) = -1.2459$ through the points $(80, 1.2703)$ and $(60,1.7975)$. (Fig. 3).

At $t = 40$ these corner points yield the following radii:

$(80, 1.5151) \rightarrow 10.87$; $(60, 2.1434) \rightarrow 11.71$;
$(80, 1.2703) \rightarrow 11.65$; $(60, 1.7975) \rightarrow 12.37$.

Thus trees in the 9 inch class at $t = 30$ will yield trees in the 10, 11 and 12 inch classes at $t = 40$.

The line given by $\beta \ln(40/\alpha) = -1.2459$ falls entirely ouside the region of interest (Fig. 3). We therefore focus on $j = 11$, $r_j = 0.55$, $f_r = -1.0209$, $r_{j1} = 0.6$, $f_{r_{j1}} = -0.8068$.

The line given by $\beta \ln(40/\alpha) = -1.0209$ passes through the points $(80, 1.4729)$ and $(60, 2.5180)$ and intersects with $\beta \ln(30/\alpha) = -1.4860$ at $(75.22, 1.6166)$ while the line given by $\beta \ln(40/\alpha) = -.8068$ passes through the points $(80, 1.1640)$ and $(60, 1.9898)$ and intersects with $\beta \ln(30/\alpha) = -1.2459$ at $(67.86, 1.5264)$.

By determining the appropriate areas the probabilities of being in the 9 inch class at $t = 30$ and the 10 and 12 inch classes at $t = 40$ are 0.0027 and .0160 respectively. As before,

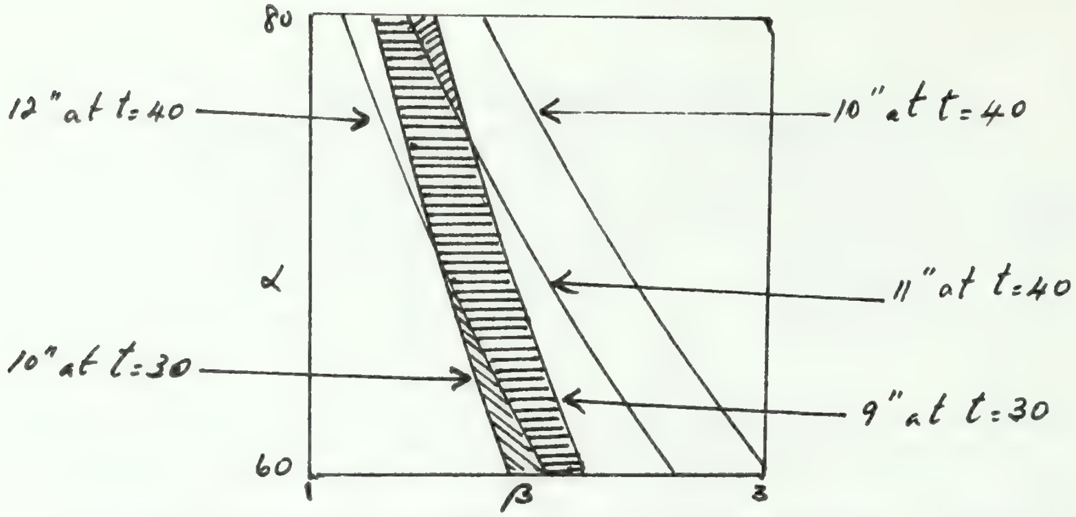

Figure 3. Areas of integration for developing transition probabilities

the probability of being in the 9 inch class at t = 30 is 0.1458; hence the probability of passing from the 9 in class at t = 30 to the 10 inch class at t = 40 is 0.0027/0.1458 = 1.84% while the probability of passing to the 12 inch class is 0.0160/0.1458 = 10.94%. The probabiliy of passing into the 11 inch class is most conveniently obtained by subtraction as 87.22%, but also can be obtained by computing the appropriate area.

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In this way the transition probabilities of Table 3 have been generated.

Let $\underline{u}'$ be the row vector $[u_i]$ where u_i denotes the probability of being in the ith radius class at time t and P = $[p_{ij}]$ where p_{ij} denotes the probability of moving from class i at time t to class j at time t + δ. Let v_j be the proability of being in class j at time t + δ and $\underline{v}'$ denote the row vector $[v_j]$. Then $\underline{v} = P'\underline{u}$. Thus we may use the transition probability matrices and the radial distributions at t = 10, 30, 50 to obtain the radial distributions at t = 20, 40, 60 (Table 4). These, of course, could also be obtained directly.

Table 3
Transition probabilities

$t = 10, \delta = 10$

j

i	2	3	4	5	6	7	8	9	10
1	1.0								
2	.1156	.5570	.3274						
3			.4013	.5917	.0070				
4				.1845	.7781	.0374			
5					.1048	.8501	.0451		
6						.1009	.8784	.0207	
7							.1627	.8373	
8								.4208	.5792

$t = 30, \delta = 10$

j

i	6	7	8	9	10	11	12	13
4	.0685	.9315						
5		.4317	.5683					
6			.3614	.6131	.0255			
7				.4413	.5587			
8					.6565	.3435		
9					.0187	.8722	.1094	
10						.1422	.8544	.0034
11							.4842	.5158
13								1.0

$t = 50, \delta = 10$

j

i	11	12	13	14	15
9	.1913	.8087			
10		.7401	.2599		
11		.0152	.8006	.1842	
12			.1852	.6491	.1657
13				.5385	.4615
14				.0167	.9833

The transition probabilities are, clearly, functions of t as well as the before and after diameter classes. Let us look more closely at an example. Consider a 7 inch radius tree at $t = 10$ and at $t = 40$. The former can be looked on as a "forerunner", the latter as a "straggler". What happens to such trees after $\delta = 10$ years. The α and β that give rise to a 7 inch tree at age 10 must lie within the rectangle defined by (L_α, U_α) and (L_β, U_β) and on the line $\beta \ln(10/\alpha) = -2.3050$. The extreme points are thus (76.52, 1) and (60, 1.1358). Thus the range of radii emcompassed at $t = 20$ by these trees would be 9.59 - 9.99 inches. On the other hand the α and β that give rise to a 7 inch tree at $t = 40$ must lie within the same rectangle and on the line given by $\beta \ln(40/\alpha) = -2.0350$. The corner points are thus (80, 2.9359) and (78.82,3). The range encompassed by these trees at $t = 50$ is then 9.43 - 9.49 inches. Thus, in this example, while the growth rate of the stragglers is less that that of the foreruners of the same initial size, the difference here is far from substantial.

Table 4
Radial distribution by one inch classes (%)

		t	
Class	20	40	60
2 - 3	4.48		
3 - 4	16.93		
4 - 5	18.41		
5 - 6	15.25		
6 - 7	13.11	.10	
7 - 8	11.59	5.68	
8 - 9	10.48	11.80	
9 -10	8.25	17.85	
10 -11	1.49	20.43	
11 -12		19.92	.37
12- 13		17.74	8.80
13 -14		6.49	20.83
14 -15			36.73
15 -16			33.26

DISCUSSION

Admittedly all this is very artificial. Our purpose has been to explore the methodological approach of assuming a certain form for the growth function of individual trees where the parameters of the function can be thought of a random variables. We have considered only one functional form, but a parallel approach would apply whatever the assumed functional form. Some forms will, of course, be more tractable than others.

We have also observed that a good start may be made by considering the parameters to be uniformly distributed over some specified range. The results for arbitrary distributions can be approximated by weighted mixtures of such uniform distributions.

Under such models we have shown how the radial (or diameter) distribution at time t may be derived and also the transition probability matrix, i.e. the probability of moving from a specified diameter class at one time to another specied diameter class at a specified future time. Diameter distributions and transition probabilities are observables. Accordingly we may manipulate models so that the resultant observables match actual data while, of course, keeping the parameters, which have some biophysical interpretation, such as R_f, within the feasible range. To fit models of this type to data, in the usual manner, is clearly impractical. However, given the computing power currently available, it would not be difficult to generate the "observables" for a range of functional and distributional assumptions. If it turns out that different assumptions give rise to similar observables, then it is clear that it will be difficult, if not impossible, to make inferences about the nature of the process from the observed data alone.

It will probably be necessary to incorporate, and the approach permits the incorporation of, additional features. For example, in the above mortality was nowhere considered. It could be brought in by introducing a probability of death as a function of diameter and/or age. Unequal ages may be looked after by, in effect, placing a distribution on t, i.e. at any time there is a range of t (= age). Effects of disturbances, such as pest or pathogen infestations, thinning, fertilization, might be accomodated by a change in the parameters at the appropriate time(s); this could be simply a shift in the mean of the parameter distribution or even a change in distributional form. It may be possible to handle the effects of pollution in a like manner.

To sum up therefore, there is no claim that what is presented here is the answer; its intent is, however, to illustrate how one may go about examining the consequences of a class of models that seemingly have relevance in modelling the growth of trees and the stands that contain them. It also seems reasonable to suggest that by constructing the observable outcomes of a range of such models one could gain insight into the feasability of various models to describe a particular data set. It is also clear that, if essentially the same observables arise under two basically different mechanisms, the selection of a model on the basis of the data alone would not be a reasonable course of action.

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GENERIC GRAPHICAL ANALYSES FOR TREE GROWTH MODEL INVALIDATION

Hans R. Zuuring, James D. Arney and Kelsey S. Milner[1]

ABSTRACT. Resource analysts, biometricians and mensurationists are often building tree growth models. The final step in any model building effort involves testing the ability of the model to reliably predict the dependent variable of interest. This model invalidation phase requires the use of a new independent data set consisting of independent variables whose ranges cover those encountered in model applications. Often graphical (residual) analyses are employed to examine a particular model's response variable behaviour. A set of standardized graphical analyses is proposed which demonstrate clearly and simply the existence and nature of a model's robustness and shortcomings. Further, we outline the criteria that must be met by any independent data set so that reliable and meaningful results can be obtained from the invalidation phase.

INTRODUCTION

In January 1985 a committee, consisting of Don Reimer, Al Stage, Kelsey Milner and Jim Arney, was formed by the Inland Northwest Growth and Yield (INGY) Cooperative to develop a set of recommendations for model performance reports. After several brainstorm session held over the next year and a half and an expanded committee membership (which included Jim Newberry, Don Patterson, Bob Pfister and Hans Zuuring) a set of minimum standards for growth model validation (actually invalidation if you think about it) projects was proposed and later accepted by the Coop membership. This paper presents the standards developed by the above group of people.

BACKGROUND

When the INGY Cooperative was formed, one of the first tasks was to identify and prioritize a set of problem areas. Growth model validation was one such identified area receiving a very high priority. As various growth model validation studies proceeded, it quickly became evident that some standardized procedures had to be developed so that various study results could be compared. Although numerous articles have been written on the evaluation

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f growth projection systems with specific reference to model erformance (Ek and Monserud, 1979; Goulding, 1979; Reynolds et l., 1981) none have provided a satisfactory solution to the roblem. Buchman and Shifley (1983) gave very useful advice to anagers by suggesting that each candidate projection system be xamined separately from the standpoint of design, performance, nd application environment. Brand and Holdaway (1983) stated hat modelers should provide extensive performance information. user should be able to learn about a model's predictive capa-ilities without needing specialized statistical knowledge.

o address the issue of model performance within the context of he INGY Cooperative, an Ad Hoc committee was formed to deal with he issue. Starting from basic statistical methods and utilizing he combined expertise of the whole group a standardized process as set forth by consensus. First the definitions of various sta-istical terms were clarified and then it was decided WHAT and HOW pecific data sets would be graphically displayed in a residual nalysis. Finally the criteria necessary to make an independent ata set useful in any validation process were also identified by he group (Arney, 1986; INGY Cooperative, 1986) and augmented by he authors through their own experiences.

RESIDUAL ANALYSIS DEFINITION AND PURPOSE

lthough statistical textbooks (Draper and Smith, 1981; Kleinbaum nd Kupper, 1978) define a residual as observed Y minus predicted , some authors have defined a residual as predicted minus observ-d. This latter definition was introduced so that any plot of esiduals having points above the X-axis would indicate a model hich overestimates and the reverse for points below the X-axis. his move may appeal to the field forester but opposes regression heory. After much debate, we adopted the traditional definition f a residual which is that a positive residual implies model nderestimation (it is all a matter of the observer's reference oint: if the X-axis is viewed as a line where there is perfect rediction then that reference line is below [underestimate] and bove [over-estimate] some of the residuals) (Figure. 1).

residual analysis is performed to show that the underlying as-umptions on which the growth model prediction equation is based annot be denied (Remember in hypothesis testing we assume the odel to be correct and we need only identify that sample data set hat will reject or invalidate the hypothesis under test). This nalysis is mostly qualitative and utilizes visual examination of raphs to detect the presence of systematic errors (bias). A re-idual analysis can be applied to any situation where a model is itted and measures of unexplained variation are available for ex-mination. Usually various 2-dimensional graphical displays with esiduals (ordinary or standardized) on the Y-axis and a specific ndependent variable (whether included in or excluded from the odel) or time measure on the X-axis are examined visually to de-ect trends. Through the recognition of certain pattern various

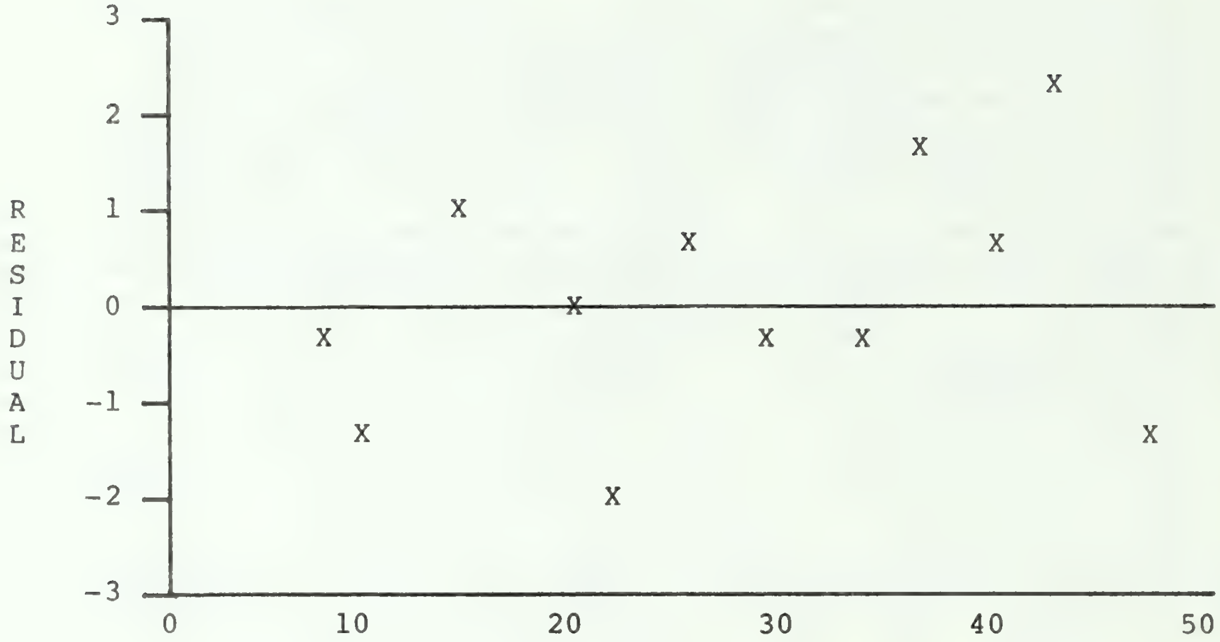

Figure 1. Representative plot of residuals (Obs - Pred) versus predicted Y.

problems with the growth prediction equation can be isolated and possibly corrected. Examples of problems are incorrect model form, nonconstant variation in Y at different levels of X (heterogeneous variance), serial correlation, identification of outliers and influential observations.

A residual analysis can also be conducted to determine the suitability of a model for a particular application. However no hard and fast rules exist to help a person or organization decide the appropriateness of a model in such a situation. Final acceptance is often subjective eventhough rigorous statistical analyses were employed to derive the model.

To facilitate the interpretation of analyses, both the format and the content of the presentation must be tailored so that both the analyst(s) and the decision-maker(s) can perceive the proper and correct meaning.

With the aid of a microcomputer and the appropriate software residuals can be plotted quickly and easily. The problem arises when a decision must be made regarding which residual to plot against which X-axis variable.

STANDARD RESIDUAL DISPLAYS

When a large number of points is displayed on a residual plot their abundance can obscure or hide any pattern that might exist. To prevent this situation the residuals should be stratified into 4 or 5 groups based on the X-axis variable. The number of observations per group need not be equal. Within each strata the mean residual and its associated standard error are calculated and then plotted as a vertical bar indicating the mean and ± 2 standard errors (Figure 2). Alternatively the median and the 30th and 70th percentiles could be calculated and displayed since these statistics are not sensitive to outliers.

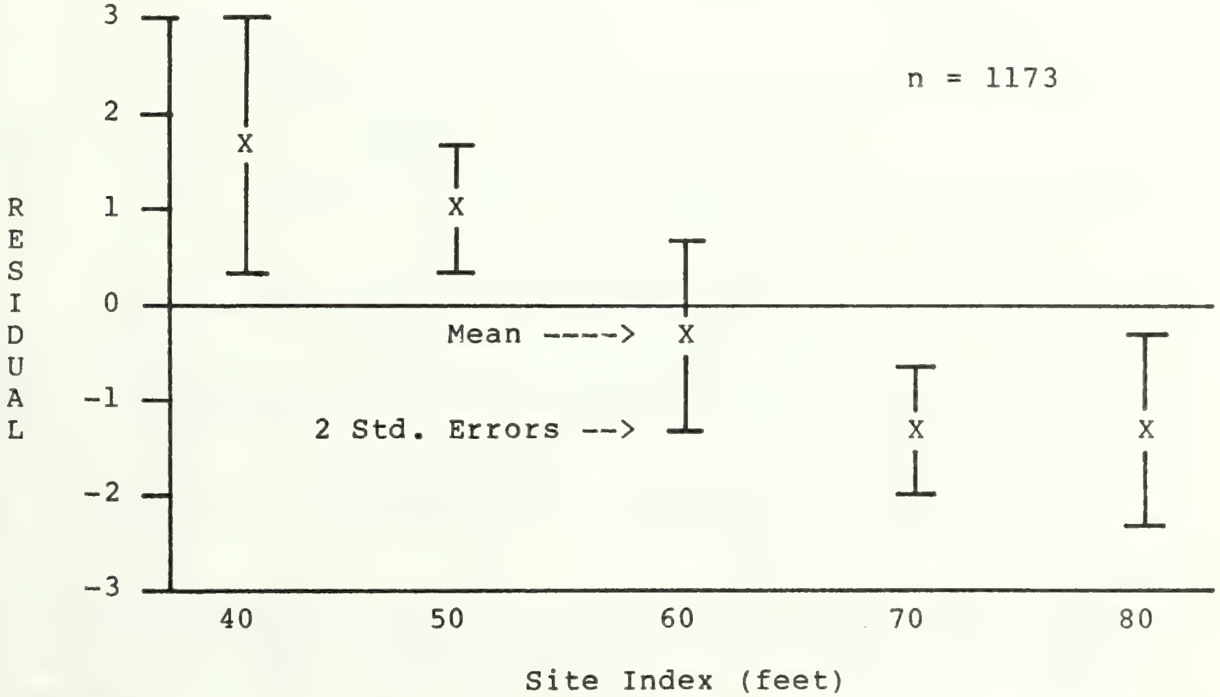

Figure 2. DBH increment growth model residuals versus five Site Index classes

Depending on the type of growth model (Whole or Component) that is being validated the following graphs are constructed by displaying each of the listed dependent variables (residual) against each independent variable:

I. Whole Model

A. Dependent Variable (Y-axis):

1) Ending average DBH residual
2) Ending top height residual

3) Ending tree/acre residual
4) Ending stand volume residual

B. Independent Variable (X-axis):

1) Initial average DBH
2) Initial trees/acre
3) Initial relative density (RD)[2]
4) Initial top height
5) Site index

NOTE: In addition whole model residual analyses will be made with and without actual mortality input if a mortality component is present in the growth model.

II. Component Model

A. Dependent Variable (Y-axis):

1) tree DBH increment residual
2) tree height increment residual

B. Independent Variable (X-axis):

1) predicted DBH or height increment
2) initial average DBH or height
3) initial top height
4) initial stand density (CCF, BA or RD)
5) initial site index

C. Tree frequency by DBH class for both observed and predicted ending stand table distributions.

NOTE: Initial and ending refers to the beginning and end of the observed growth period (usually 5 or 10 years) found in data sets compiled from permanent growth plots (CFI or other sources) which have been remeasured several times. A set of graphs is reproduced for each major tree species.

DATA SET REQUIREMENTS

Both the data set used to develop a growth model and the one employed to test (invalidate) the model should include the following items:

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[2] Relative density is defined as $BA/sqr(D_{mv})$
where BA = basal area/acre
D_{mv} = DBH for tree of median volume

A. Descriptions

1) geographic location
2) study designs
3) plot sizes
4) measurement standards
5) data sources
6) time periods of data collection
7) rules for data rejection

B. Tables and Reports

1) plot data
2) tree data
3) for each variable (dependent and independent):

    i. compute the following statistics: arithmetic mean, standard error, minimum and maximum value , number of observations.

    ii. display histograms of the frequency of observations (all plot data) by preselected class intervals based on site index, initial DBH, initial top height, initial stand density and initial relative density (RD).

With respect to tree data a few comments are in order. It is desirable to have the heights of all recognized plot trees, regardless of species, but knowing that this is not operationally feasible, a minimum of 6 to 10 heights should be available across a range of DBHs for each species. This way, reliable HT - DBH relationships (one for each species) can be estimated. Further a plot should only be used when the species of interest comprises 30% or higher of the plot BA. Plots should only be selected if no fire or insects and disease are present; no logging has taken place in the last 10 years; the site is uniform. Otherwise HTs, DBHs and stand density will be drastically altered. Such data sets should not be used to test a growth model that cannot handle such events.

CONCLUSIONS

Minimum residual analysis standards as well as desirable test data set characteristics were defined by the Ad Hoc committee of the INGY Cooperative so that various growth model validation results could be compared. By defining the use to which a growth model is put, the appropriate validation process can be selected so that the resultant information has the greatest utility.

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A GROWTH AND YIELD PREDICTION SYSTEM WITH A MERCHANDISING OPTIMIZER FOR PLANTED LOBLOLLY PINE IN THE WEST GULF REGION

V. C. Baldwin Jr. and R. L. Busby[1]

ABSTRACT. A growth and yield prediction system with a merchandising optimizer is described for use in thinned or unthinned loblolly pine (Pinus taeda L.) plantations in the west gulf region. This system can be used to forecast weight and volume yields for stands partitioned into 1-inch d.b.h. classes at any stage of plantation development from ages 10 through 50. The data for the prediction system came from 859 measurements of thinned and unthinned long-term research study plots on cutover sites located in east Texas, Louisiana, and southern Mississippi. The merchandising optimizer converts stand tables predicted using the three-parameter Weibull function into an estimated product mix by using a dynamic programming algorithm that maximizes the selling value of the stand. The algorithm divides the stand table into seven possible products. The computer program that operates the system, COMPUTE_MERCHLOB, is available from the authors.

INTRODUCTION

Loblolly pine (Pinus taeda L.) is the most important commercial softwood species in the South and the most widely planted southern pine. Managers of loblolly pine plantations need accurate and complete predictions of tree component growth and yield by weight or volume in various product classes in order to formulate flexible management policies and to predict expected monetary returns for the optimum product alternatives. For example, the decision of whether or not to thin must be made. If the decision is to thin, questions arise as to when, how much, and how often to thin. To answer these questions, a forest manager needs information regarding the economic aspects as well as the biological aspects of the future stand. One needs to know not only the total amount of wood or biomass that can be produced, but what products might be produced from the total harvest. In other words, the stand must be premerchandised. There is a critical need for this kind of information on cutover and prepared sites in the west gulf region.

A new yield prediction system for thinned and unthinned loblolly pine plantations has recently been developed for the west gulf region (Baldwin and Feduccia 1987). The computer program for this new system is called COMPUTE_P-LOB, Comprehensive Outlook for Managed Pines Using simulated

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Treatment Experiments for Plantation Loblolly Pine (Ferguson and Baldwin 1987). This growth and yield prediction system provides both weight and volume yields in a stand/stock table format for the aboveground portion of the trees by 1-inch d.b.h. classes for 10- to 50-year-old loblolly pines grown in plantations on cutover sites. However, many users have expressed a desire that yields be separated into possible product classes.

Recently, Busby and Ward[2] developed a merchandising optimization routine called MERCHOP for use with growth and yield prediction systems in order to give users a wider selection of product categories and to provide them with mathematically derived optimum product mixes for any given yield output. Their algorithm divides a stand table into seven products: poles, veneer bolts, saw logs, chip-n-saw logs, pulpwood bolts, chips, and residual wood. Users specify product prices, maximum and minimum product sizes, minimum product harvest per-acre volumes, and a factor to account for degrade due to form and other defects.

The merging of the Baldwin and Feduccia growth and yield prediction system (COMPUTE_P-LOB) with the Busby and Ward merchandising optimizer MERCHOP is described in this paper. The computer program for this combined system is called COMPUTE_MERCHLOB. It represents the first attempt to merge MERCHOP with a thinned stand growth and yield prediction system. Baldwin and Feduccia (1987) can be referred to for detailed data information, modeling philosophy, models, and equation coefficients for the yield prediction system.

GROWTH AND YIELD MODELING

DATA

The growth and yield model is based on measurement data taken from study plots in unthinned and thinned loblolly pine plantations established on cutover longleaf pine (Pinus palustris Mill.) forest land. Initial survival for these plantations had been good and there had been low levels of insect and disease problems. The long-term studies produced 224 growth measurements from 85 unthinned stand plots and 534 growth measurements from 178 thinned stand plots. All plots were located in east Texas, north and central Louisiana, and eastern Mississippi. Plot age (from time of planting) ranged from 10 through 45 years, site index (base age 25) from 40 to 90 feet, and planting density from 1,090 to 2,700 trees per acre. The thinning interval for stands in the long-term studies had been 5 years, and residual densities after thinning had ranged from 50 to 130 square feet of basal area.

DIAMETER DISTRIBUTION PROCESS

The three-parameter Weibull function (Bailey and Dell 1973) was selected as the model to describe the d.b.h. distribution in a plantation. At any given time in a stand's development the minimum (X(1)), quadratic mean (X(qmd)), and 93rd percentile (X(93)) stand diameters were predicted as functions of number of trees surviving (TS) and stand age from planting (A), dominant height (HD), or site index (SI). Weibull parameters were then estimated by solving those equations using algebraic and numerical techniques as explained in Baldwin and Feduccia (1987). Thus, given the prediction of the number of trees surviving, the total number of trees can be partitioned into 1-inch d.b.h. classes and a stand table can be constructed.

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[2] Busby, Rodney L. and Keith Ward. A users guide to MERCHOP (manuscript in preparation)

GROWTH AND YIELD PREDICTION SYSTEM OPTIONS

This prediction system allows a user to initiate the process by beginning and ending with an unthinned stand, beginning with an unthinned stand, and ending with a stand thinned one or more times, or beginning with a previously thinned stand and ending with a stand thinned one or more times. Figure 1 summarizes the prediction system process.

YIELD PREDICTIONS IN UNTHINNED STANDS

Required input information when starting with an unthinned stand are A, HD, and TS. If HD is not available as an input, it is predicted using a SI function rearranged to predict HD. If TS is not known it can be predicted as a function of TP (trees planted per acre), A, and HD or as a function of HD and BA (basal area per acre).

Given this initial information, the current stand is described by the prediction of X(1), X(qmd), and X(93) as functions of HD, TS, and A. Then the Weibull parameters are estimated and stand/stock tables are produced through the process described in the diameter distribution process section.

Predictions of future stand attributes and future stand/stock table information in unthinned stands is accomplished first by projecting TS from time A(1) to time A(2) using a survival function TS(2) = f[TS(1), SI, A(1), A(2)]. The site index equation is then employed to obtain HD(2) at A(2). Finally, these values are used as predictors in the equations mentioned above to obtain X(1), X(qmd), and X(93) at time A(2). New Weibull parameters are estimated and a new stand/stock table is derived.

PREDICTING STAND ATTRIBUTES AFTER THINNING

The residual stand after thinning is determined by prediction of "thinned" values for X(1,a), X(qmd,a), X(93,a), TS(a), and BA(a) (the subscript "a" denotes an after thinning value) followed by numerical solution of the first three prediction equations to obtain the Weibull parameters, as already explained. Only equations to model the low thinning used in the stands under study were developed because sufficient data were not available to model other types of thinning. Since there was a significant difference in the resulting stand after the first thinning as compared to stands following subsequent thinnings, two separate sets of equations were developed: one set to predict the stand characteristics following the first thinning and the other set to be used to predict the residual stand after any subsequent thinning.

The target density for each thinning may be in terms of a residual stand BA or TS. The equations for X(1,a), X(qmd,a), X(93,a) were all developed as functions of the before-thinned values of the predictor variable, HD(b), and

$BA(a)/BA(b)$ (the subscript "b" denotes a before thinning value). If the thinning target were chosen instead to be $TS(a)$, the value for $BA(a)$ was first predicted from an equation relating $TS(a)/TS(b) = f[BA(a)/BA(b)]$.

YIELD PREDICTIONS FOR THINNED STANDS

Equations in the thinned stand section of the yield system take either predicted or user-supplied after-thinning stand information at age $A(1)$ and project these values into the future to $A(2)$ to provide stand table predictions at the new stand age. The same stand diameter and height attributes as used elsewhere are also predicted here, and these values are used to obtain Weibull parameters to describe the new stand.

The diameters predicted at a second age (subscript 2) in thinned stands ($X(1,2)$, $X(qmd,2)$, and $X(93,2)$) are all obtained from equations that utilize the initial values of the predicted variables $X(1,1)$, $X(qmd,1)$, or $X(93,1)$, and $TS(1)$, $A(1)$, and $A(2)$. For prediction of survival in thinned stands, a survival equation $TS(2) = f[TS(1), SI, A(1), A(2)]$ is used.

STAND/STOCK TABLE CONSTRUCTION

Stand tables are generated for any age by apportioning the total number of surviving trees into 1-inch d.b.h. classes according to the predicted Weibull distribution for that age. Development of a stock table requires a total-height prediction equation, volume or weight equations, and taper equations. Two height prediction equations, one for trees from unthinned stands and one for trees from thinned stands, were developed. They predict total tree height as a function of d.b.h., HD, A, and TS. The volume, volume ratio, weight, weight ratio, and taper equations are described in detail in Baldwin and Feduccia (1987).

MERCHANDISING OPTIMIZER

INPUT OPTIONS AND REQUIREMENTS

The model allows the user to specify up to six different products: (1) poles, (2) veneer bolts, (3) saw logs, (4) chip-n-saw logs, (5) pulpwood bolts, and (6) chips. Residual wood is used if the chips category is not used because the model requires that the entire bole of the tree be accounted for. The units of measurement for each product may be: tons; cords; board feet, Doyle; board feet, Scribner; or board feet, International 1/4 inch; depending upon the type of product being produced.
Price and product dimensions must next be specified. Price per unit by product, minimum and maximum top-end diameters, minimum and maximum piece lengths, the piece length increment, and allowance for trim must be specified. These inputs allow the user to specify the size and value for each product. For example, the user could say that poles must have a top-end diameter between 4 and 10 inches and be between 40 and 70 feet in length. Note the user is asked only to define possible products.
The problem of how to best allocate the production of the various products will be solved by the model.

Two problems arise when attempting to estimate the value of projected stands based on growth and yield models: (1) form and disease product degrade information are not provided, and (2) small quantities of even high-valued products may be too expensive to sort out and sell. Form and disease product degrade may be modeled by inclusion of the input variable NPRCNT, defined as the maximum percentage of properly sized trees suitable to make a product (poles, veneer logs, etc.). For example, not all trees 40 feet tall to a 6-inch top are suitable for pole production because some may have bad form or disease-induced degrade. Therefore, the user can set NPRCNT to, say, 10 percent if it is presumed that only 10 percent of such trees might be suitable for pole production. The purpose of NPRCNT is to allow the user to simulate the effects of defects. The estimate of the value of a stand will be too high if the form and disease product degrade is ignored. Thus, NPRCNT must be set for each product, and it must range between zero and 100 percent.

The final output variable, HARVST, sets the minimum harvest necessary for any product to be produced. A timber stand may contain low volumes of a high-value product, but that product might not be economical to produce because of high sorting costs. For example, the user may specify that a minimum of 1,000 board feet per acre of sawtimber must be produced if the product is to be produced at all. This procedure allows the user to model the effects of sorting costs without having to input extensive logging and sorting cost information into the model.

THE MERCHANDISING AND OPTIMIZATION PROCESS

Once the input has been specified, the model uses dynamic programming to find the "highest valued" product mix from either the cut table or the stand table provided by the growth and yield subroutines. Dynamic programming is a mathematical technique designed primarily to improve the computational efficiency of certain optimization problems (Taha 1976). The basic idea of the technique is to decompose the optimization problem into smaller subproblems that are computationally more manageable. An alternative to dynamic programming is to simply list all possible combinations of products that could be produced from the stand, and then pick the combination of products that produce the best result.

Representative trees are used for each d.b.h. class. The dynamic programming subroutines divide the tree into sections, and the optimal method of bucking the tree is found by using the growth and yield model's height and taper functions and the user's list of potential products. A set of such solutions is actually calculated since more than one bucking pattern will be used when total volumes are estimated. One by one, products are dropped from the user's list of potential products. The result is a set of solutions showing the best bucking patterns for several sets of products.

For example, suppose that a user specified three possible stand products: poles, sawlogs and chips. The dynamic programming algorithm would find the optimum bucking pattern for three sets of products: (1) poles, sawtimber, and chips; (2) sawtimber and chips; and (3) chips. If all trees could produce all products, or NPRCNT were set to 100 percent each for poles, saw logs, and chips, total production for the d.b.h. class would be calculated by multiplying the total number of trees in the d.b.h. class by the product volumes corresponding to the optimum bucking pattern that used all three products. If NPRCNT were set at less than 100 percent for any of the products, total production for the d.b.h. class would be calculated by multiplying the appropriate number of trees times the the product volumes corresponding to the appropriate bucking pattern. Suppose the user set NPRCNT at 20 percent for poles, 70 percent for sawlogs, and 100 percent for chips. In a d.b.h. class that contained 100 trees, 20 trees would be assumed to be free enough from defects to be able to produce poles, although those trees could also produce saw logs or chips. Seventy trees are assumed free enough of defects to produce saw logs, although they might also produce chips. Finally, it would be assumed all 100 trees could produce chips. In order to calculate total production for that d.b.h. class under those conditions, the optimal bucking pattern that picked among all the possible products would be selected first and used on 20 trees (20 percent of 100 trees), and the productivity would be calculated as 20 times the product volumes corresponding to that bucking pattern. Next, the optimum bucking pattern for saw logs and chips would be used on 50 trees (70 percent of 100 trees minus the 20 already used), and the productivity calculated as 50 times the product volumes corresponding to that bucking pattern. The remaining 30 trees (100 trees minus the 70 already used) would be allocated to chip production and the chip productivity determined by multiplying 30 times the volume obtainable through chipping only.

Total stand production is the sum of the production of each d.b.h. class. If any product fails to meet the minimum harvest levels per acre (HARVST), the entire optimization problem is rerun, excluding that particular product from consideration. The result is a model that predicts the value of a thinning or final harvest stand given the scenario modeled by the user.

DISCUSSION AND CONCLUSIONS

Diameter distribution and individual-tree-based growth and yield prediction systems will each provide stand and stock table output. Some, such as COMPUTE_P-LOB, include weight as well as volume yields. These features go a long way towards providing a forest manager with future product yield predictions. However, economic and product specification information are also needed in order to effectively merchandise a stand: this latter information is critical in the planning process. A method is needed to estimate the economic impact of proposed management practices (such as thinning), which will not only alter total volume and weight yields, but will also alter the size and shape of tree boles and the ratio of branchwood to bolewood. Thinning changes the product mix of a stand that will finally be harvested. COMPUTE_MERCHLOB was created to help fulfill some of these management needs.

COMPUTE_MERCHLOB's output at each output stage consists of two tables--a product yield table divided into the product possibilities specified and a value table providing predicted monetary amounts for the products. These represent the highest-value solutions, subject to the constraints imposed by the users. This information, used in conjuction with or in place of regular stand and stock table outputs, can then be used to make the management decisions critical in running a profitable wood products business venture using loblolly pine from plantations in the west gulf region.

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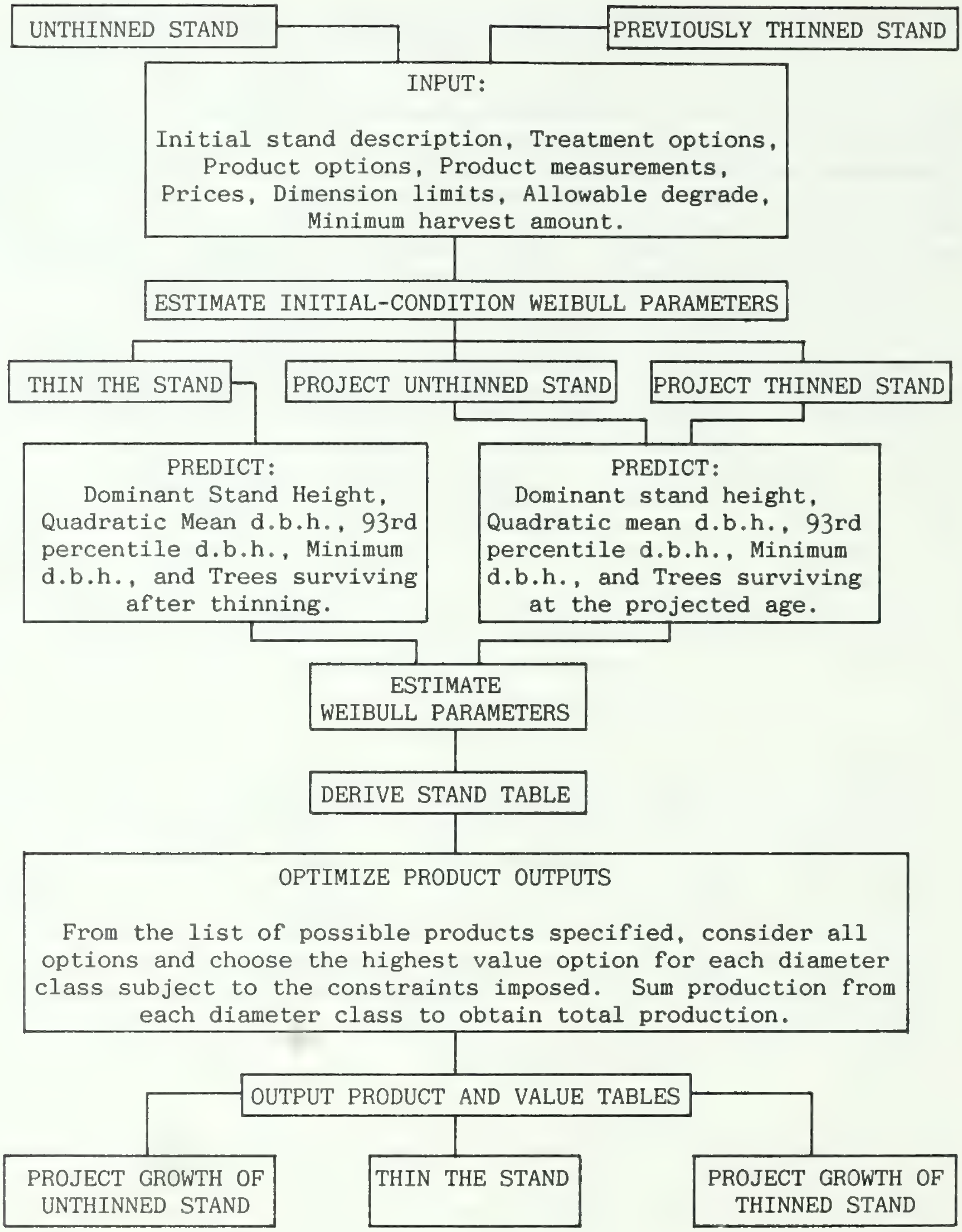
UNTHINNED STAND
PREVIOUSLY THINNED STAND
INPUT:
Initial stand description, Treatment options, Product options, Product measurements, Prices, Dimension limits, Allowable degrade, Minimum harvest amount.
ESTIMATE INITIAL-CONDITION WEIBULL PARAMETERS
THIN THE STAND
PROJECT UNTHINNED STAND
PROJECT THINNED STAND
PREDICT: Dominant Stand Height, Quadratic Mean d.b.h., 93rd percentile d.b.h., Minimum d.b.h., and Trees surviving after thinning.
PREDICT: Dominant stand height, Quadratic mean d.b.h., 93rd percentile d.b.h., Minimum d.b.h., and Trees surviving at the projected age.
ESTIMATE WEIBULL PARAMETERS
DERIVE STAND TABLE
OPTIMIZE PRODUCT OUTPUTS
From the list of possible products specified, consider all options and choose the highest value option for each diameter class subject to the constraints imposed. Sum production from each diameter class to obtain total production.
OUTPUT PRODUCT AND VALUE TABLES
PROJECT GROWTH OF UNTHINNED STAND
THIN THE STAND
PROJECT GROWTH OF THINNED STAND

Figure 1. Schematic diagram summarizing the operation of the yield prediction system and the merchandising optimizer through one output cycle.

USING A DIRECT SEARCH ALGORITHM TO OPTIMIZE SPECIES COMPOSITION IN UNEVEN-AGED FOREST STANDS

B. Bruce Bare and Daniel Opalach[1]

ABSTRACT. Describes an approach for determining the optimal sustainable equilibrium diameter distribution and species composition for uneven-aged forest stands. A direct search, derivative free, constrained nonlinear programming algorithm is applied to a deterministic version of the Stand Prognosis Model. The diameter distribution for each species is described by a two-parameter Weibull distribution and the number of trees per acre. The optimization problem is formulated in terms of these three decision variables per species. Results are presented for both board and cubic foot growth objective functions, and the species composition is allowed to consist of one to three species. Few of the optimal solutions produce balanced diameter distributions, although all are sustainable over the cutting cycle. Solutions involving a mixture of the three permissable species produce more volume growth than do either the one or two species alternatives.

INTRODUCTION

Determining the optimal sustainable equilibrium diameter distribution for an uneven-aged mixed-species forest stand is one of the major decisions facing forest managers (Hann and Bare, 1979). Yet, only recently have forest researchers begun to address these problems (e.g., Bare and Opalach, 1987; Haight, 1985, 1987; Hansen and Nyland, 1987; Martin, 1982; Adams and Ek, 1974). Using a deterministic version of the Stand Prognosis Model, a distance independent individual tree growth model with species-dependent growth dynamics, this paper discusses a procedure for determining the optimal sustainable equilibrium diameter distribution and species composition for uneven-aged forest stands. For comparative purposes, optimal solutions are derived for both board and cubic foot growth objectives consisting of one to three species.

MODEL DEVELOPMENT

The deterministic version of the Stand Prognosis Model developed for purposes of optimization consists of three parts: (1) large and small tree diameter increment functions, (2) mortality functions, and (3) regeneration functions. Diameter increment functions are taken from Wykoff (1986), but random perturbations are excluded. Mortality functions are taken from Wykoff et al. (1982) and Wykoff (1986). In the Prognosis Model, trees are removed from the tree list if their probability of survival compares unfavorably with a randomly drawn number. However, the deterministic version of the Prognosis Model keeps

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track of the number of trees per acre represented by each tree on the list. At the end of each ten-year projection period, the number of trees per acre represented by each tree on the list is updated by multiplying its "survival tree factor" by the computed probability of survival. This method for assigning mortality is very similar to the deterministic mortality option of the STEMS growth projection system (Belcher et al., 1982).

Regeneration functions are derived from Ferguson et al. (1986) and the FORTRAN source code for version 5.0 of the Prognosis Model. To implement regeneration functions in a deterministic manner, probabilities are viewed as proportions. For example, Ferguson et al. (1986) assign the three classes of regeneration (i.e., advance, subsequent, and excess) for each species to 1/300-acre plots by comparing random numbers to computed probabilities. In the deterministic version of the Prognosis Model, these probabilities are viewed as proportions and are multiplied by 300 to determine the number of advance, subsequent, and excess trees of each species to add to the tree list. In doing this, it is assumed that each 1/300-acre plot can have at most one advance, one subsequent, and one excess regeneration tree of a given species.

In addition to the assumptions outlined above, it is also assumed that best trees (i.e., advance and subsequent regeneration) are at least 4.5 feet in height. Best trees are a crucial component of a residual stand and are added to the tree list to determine sustainable equilibrium diameter distributions.

Given a beginning tree list (made up of one or more species), the deterministic version of the Prognosis Model first uses ten-year diameter increment functions to update tree diameters. Mortality functions are then used to compute ten-year survival proportions. Lastly, trees are added to the tree list by the regeneration subsystem and volumes are computed to evaluate the objective function. This sequence is repeated as many times as necessary to account for the cutting cycle being evaluated.

The sustainable equilibrium diameter distribution for each species is modeled by a two-parameter Weibull distribution function. Thus, the optimization problem is formulated in terms of three decision variables per species: (1) the scale and shape parameters of the Weibull distribution, and (2) the total number of trees per acre. As described later, a tree list is constructed for each set of these decision variables generated during the optimization process.

Box's complex algorithm (Kuester and Mize, 1973) is used to solve the optimization problem. The first step in the optimization process is to construct an initial complex. This is a set of points in decision space, which consists of 3*K dimensions, where K is the number of species being considered for the residual stand. Associated with each point in the complex is an objective function value. Initially, the points in the complex are generated to ensure broad coverage of the decision space, and for each point in the initial complex, a tree list is constructed. This tree list is passed to the deterministic version of the Prognosis Model and an updated tree list is returned representing the status of the stand at the end of the cutting cycle. After evaluating the objective function, the equilibrium sustainability constraint is checked and the objective function value is penalized if the constraint is violated.

Twenty-one solutions are used to construct the initial complex for the three species optimization problem. The algorithm then begins an iterative search to locate the optimal solution. The point in the complex with the lowest objective function value is omitted and the centroid of the remaining points is computed. The lowest-valued point and the centroid are then used to define the search direction, and a new solution is located in this direction. This new solution is used to generate a new tree list and the deterministic version of the Prognosis Model is used to update the list and provide an associated value of the objective function. This sequence continues until convergence criteria are satisfied or the number of iterations exceeds a prespecified limit.

MATHEMATICAL MODEL

The general form of the optimization model described in the previous section is:

$$\text{MAX} \quad Z_t = \sum_{s=1}^{K} \sum_{u=1}^{N'_s} V_{su} R_{su} - \sum_{s=1}^{K} \sum_{u=1}^{N_s} V_{su} R_{su}$$

Subject to:

$$X'_{ds} - X_{ds} \geq 0 \text{ for } d = 1,2,\ldots,M \quad s = 1,2,\ldots,K$$

$$B_s > 0, \quad C_s > 0, \text{ and } N_s \geq 0 \text{ for } s = 1,2,\ldots,K$$

Where,

Z_t = Per acre board (cubic) foot volume growth harvested every t-years

t = Cutting cycle ($t = 10$ NGP)

NGP = Number of ten-year growth projection periods in cutting cycle

K = Number of species in residual stand

M = Number of diameter classes used in equilibrium sustainability constraint

N_s, N'_s = Number of trees per acre of sth species at beginning and end of cutting cycle

V_{su} = Scribner board foot or cubic foot volume for uth tree, sth species

R_{su} = Survival tree factor. The number of trees per acre represented by uth tree, sth species

X_{ds}, X'_{ds} = Number of trees per acre in dth diameter class for sth species at beginning and end of cutting cycle

B_s = Weibull distribution scale parameter for sth species

C_s = Weibull distribution shape parameter for sth species

The relationship between X_{ds} and the three decision variables (B_s, C_s, and N_s) is shown in the following equation (Martin, 1982; Bailey and Dell, 1973):

$$X_{ds} = \frac{N_s \{ \exp [-(DL_{ds}/B_s)^{C_s}] - \exp [-(DU_{ds}/B_s)^{C_s}] \}}{1 - \exp [-(MD/B_s)^{C_s}]}$$

In this formula, MD, DL_{ds}, and DU_{ds} are, respectively, the diameter of the largest tree permitted in the residual diameter distribution, and the lower and upper diameter limits for the dth diameter class and sth species. For all results presented here, the width of the diameter class used in the sustainability equilibrium constraint is three inches and the maximum tree allowed in the residual stand is 27 inches. This equation is used to generate each beginning tree list by assuming that trees are uniformly distributed within each diameter class. This produces initial distributions which are approximately Weibull distributed.

RESULTS

To demonstrate the use of the model, the Abies lasiocarpa/Clintonia uniflora habitat type on the Coeur d'Alene National Forest in northern Idaho is highlighted. Species commonly found in this type include Abies lasiocarpa, Picea engelmannii, Pseudotsuga menziesii, Larix occidentalis, Pinus contorta, and Pinus monticola. Although this common forest type occurs under a wide variety of growing conditions, all results presented below assume an elevation of 4,500 feet, a slope of ten percent, and an aspect of zero degrees. Uneven-aged silvicultural systems are used in this type to favor watershed, recreation, wildlife, and amenity values (Alexander and Edminster, 1977).

At most three species--limited to the first three species in the above species list--are permitted in the residual stand. Other species entering the stand during the cutting cycle are assumed to be removed in a precommercial thinning operation during the harvest at the end of the cycle. Board foot volumes are only computed for trees ≥ 9 inches in diameter and cubic foot volumes are computed for all trees.

Analyses were conducted using a ten-year cutting cycle for both the board and cubic foot growth objectives. Tables 1 and 2 contain the steady-state diameter distributions for the three species mixture for these objectives. These solutions produce more volume growth than any of the one and two species mixture alternatives. Although Pseudotsuga is only present in the smaller diameter classes, its forced removal (see Table 3) results in a drop in both board and cubic foot growth.

A comparison of Tables 1 and 2 reveals the contrast in diameter distributions when cubic foot volume growth is maximized instead of board foot growth. As expected, fewer large trees are carried in the residual stand when cubic feet are used to measure volume growth. Thus, managerial objectives must be clearly understood prior to optimizing stand management decisions. Also, both solutions nearly extinguish Pseudotsuga from the steady-state residual stand. Evident in Tables 1 and 2 is that Abies recruitment is limiting the attainment of additional volume production.

Table 1. Three species equilibrium diameter distributions for maximum board foot volume growth.

Board Feet Per Acre Optimal Solution

Diameter (In.)	Residual Picea	 Abies	 Pseudotsuga	Harvest Picea	 Abies	 Pseudotsuga
0- 3	15.89	452.41	13.55	5.86	0.07	61.58
3- 6	4.97	112.19	0.60	0.01	0	3.07
6- 9	1.32	22.87	0	0.14	51.50	1.49
9-12	0.33	4.32	0	2.21	64.10	0.29
12-15	0.08	0.78	0	2.50	34.76	0
15-18	0.02	0.13	0	0.03	0.17	0
18-21	0	0.02	0	0.01	0.03	0
21-24	0	0	0	0	0.01	0
24-27	0	0	0	0	0	0

	Picea	Abies	Pseudotsuga	
N_s	22.61	592.72	14.15	
B_s	2.51	2.14	1.46	MAX Z_{10} = 10632 bd.ft./acre
C_s	1.08	1.08	1.60	

The shape parameter (C_s) for all three species shown in both Tables 1 and 2 does not equal one, although it is very close in Table 1 for Picea and Abies. Thus, with these exceptions, the negative exponential distribution[2] does not exactly describe the diameter distributions for the three species mixture and, therefore, the distributions are not balanced. Lastly, 185 and 155 trees per acre must be precommercially removed each cutting cycle to maintain the distributions shown in Tables 1 and 2, respectively.

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[2] The negative exponential distribution is obtained from the Weibull distribution when C equals one.

Table 2. Three species equilibrium diameter distributions for maximum cubic foot volume growth.

Cubic Feet Per Acre Optimal Solution

Diameter (In.)	Residual			Harvest		
	Picea	Abies	Pseudotsuga	Picea	Abies	Pseudotsuga
0- 3	12.65	475.55	0.59	6.81	0.01	72.46
3- 6	0.32	130.31	0.02	2.66	0.01	0.16
6- 9	0.01	5.63	0.01	1.28	77.52	0.06
9-12	0	0.07	0	0.16	64.83	0.01
12-15	0	0	0	0.08	31.58	0
15-18	0	0	0	0	0	0
18-21	0	0	0	0	0	0
21-24	0	0	0	0	0	0
24-27	0	0	0	0	0	0

N_s	12.98	611.56	0.62
B_s	0.70	2.34	0.12
C_s	0.89	1.64	0.35

MAX Z_{10} = 2220 cu.ft./acre

Table 3 illustrates the consequence of forcing Pseudotsuga from the three species solution shown in Table 1. The two species solution shown in Table 3 produces the maximum board foot volume growth of all two species mixtures examined. While not dramatically different from the solution shown in Table 1, the board foot volume growth over the ten-year cutting cycle is 249 board feet less. Further, 295 trees per acre must be precommercially removed each cutting cycle to maintain this distribution. Lastly, the diameter distributions are not balanced. As previously mentioned, the lack of Abies recruitment (and to some extent Picea) appears to be limiting the production of additional board foot volume growth for the two species mixture shown in Table 3. Although not shown, by forcing Pseudotsuga from the three species solution shown in Table 2, the maximum cubic foot volume growth for the resulting Picea-Abies mixture decreases to 2194 cubic feet per acre--a drop of only six cubic feet.

An Abies-Pseudotsuga two species mixture was also examined. The optimal board foot volume production was 10108 board feet per acre each cutting cycle and consisted of 579 and 66 trees per acre for Abies and Pseudotsuga, respectively.

Table 3. Two species equilibrium diameter distributions for maximum board foot volume growth.

Board Feet Per Acre Optimal Solution

Diameter (In.)	Residual		Harvest	
	Picea	Abies	Picea	Abies
0- 3	22.44	460.94	0.02	0.09
3- 6	3.12	118.70	1.94	0.02
6- 9	0.70	18.61	2.32	58.91
9-12	0.18	2.35	1.41	69.33
12-15	0.05	0.25	1.43	30.86
15-18	0.02	0.02	0.02	0.07
18-21	0	0	0	0.01
21-24	0	0	0	0
24-27	0	0	0	0

N_s	26.51	600.87
B_s	1.41	2.19
C_s	0.83	1.20

MAX Z_{10} = 10383 bd.ft./acre

All single species alternatives produced less volume than the two or three species mixtures. However, the single species Abies alternative only underproduced the three species mixture by 691 board feet per acre. Thus, different combinations of species appear to produce approximately equal board foot volumes.

SUMMARY

An optimization program consisting of a deterministic version of the Stand Prognosis Model and a direct search optimization algorithm is used to determine the optimal diameter distribution of each species in an uneven-aged forest stand. Results illustrate the dramatic differences in optimal diameter distributions depending on which measure of volume growth--board or cubic foot--is used in the formulation of the optimization problem. The program also has been used to solve optimization problems with economic objective functions (Bare and Opalach, 1987). Results presented in this paper and in Bare and Opalach (1987) suggest that the optimization techniques employed might be used to optimize any deterministic individual tree/distance independent growth model.

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PENALTY FUNCTION METHODS FOR CONSTRAINED HARVESTING IN UNEVEN-AGED MIXED-CONIFER STANDS

Robert G. Haight[1]

ABSTRACT. Uneven-aged management problems include the determination of the best sequence of selection harvests that terminates in a steady state. To find optimal transition harvests for irregular stands, either fixed endpoint or equilibrium endpoint constraints can be imposed after finite transition periods. Fixed and equilibrium endpoint problems are presented and compared in the context of a nonlinear stage-structured model for stand growth. For a given transition period length, the management regime that solves the equilibrium endpoint problem has a higher present value than the solution to the fixed endpoint problem. As the transition period lengthens, regimes that are constrained to achieve the extremal steady state approach the solution to the equilibrium endpoint problem. For any transition period length, management regimes that are constrained to achieve investment efficient or maximum sustainable rent steady states are suboptimal compared to regimes that converge to the extremal steady state.

INTRODUCTION

Models for uneven-aged management have been developed that allow the determination of the diameter class harvesting rates that maximize the present value of an existing stand over an extended planning horizon without steady state constraints (see Haight et al. (1985) and Haight (1985)). Optimal management regimes often involved large variations in harvest levels over time, and steady states were achieved only after long transition periods. Stand management objectives that include steady state harvesting in addition to the maximization of present value can be incorporated into a dynamic optimization model by constraining the harvest level to be in a steady state after a finite number of transition harvests. This paper formulates and compares dynamic harvesting problems that have either equilibrium endpoint constraints (e.g., Michie (1985)) or fixed endpoint constraints (e.g., Adams and Ek (1974)).

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Consider a population represented by $\mathbf{x}(t) = (x_1(t), \ldots, x_n(t))'$, where $x_i(t)$ is the number of individuals in the ith growth stage at the beginning of time period t. For biological realism constrain $\mathbf{x}(t)$ to lie in R^{+n}, the nonnegative quadrant of R^n. Assuming that the population under consideration is a resource system in which individuals can be harvested from each growth stage, define a control vector $\mathbf{u}(t) = (u_1(t), \ldots, u_n(t))'$, where $u_i(t)$ is the number of individuals harvested from the ith growth stage at the end of time period t. Since $\mathbf{u}(t)$ represents the levels at which the resource is exploited, $\mathbf{u}(t)$ belongs to a suitably defined set $U \in R^n$, where

$$U = \{\mathbf{u}(t) \in R^n \mid 0 \leq u_i(t) \leq \overline{u}_i(t),\ i = 1, \ldots, n\}, \tag{1}$$

and $\overline{u}_i(t)$ is an upper bound (maximal extraction rate) for $u_i(t)$. There is usually a practical unit of time associated with the resource system. For example, in forest growth and yield models, the time period is five or ten years depending on the remeasurement period used in the inventory system.

A stage–structured model characterizes population growth as a transformation of the state vector $\mathbf{x}(t)$ using an n–dimensional matrix model. The elements of the transition and survival matrices and the regeneration vector are scalar functions that depend on k aggregations of the elements of the state vector $\mathbf{x}(t)$. Each aggregate variable represents a measure of population density that is defined as a weighted sum of the number of individuals in each growth stage. The population density variables are denoted by the vector $\mathbf{y}(t) = (y_1(t), \ldots, y_k(t))'$ and are defined by the transformation

$$\mathbf{y}(t) = A\mathbf{x}(t) \tag{2}$$

where A is a $k \times n$ matrix with elements $a_{ij},\ i = 1, \ldots, k,\ j = 1, \ldots, n$.

The elements of the survival and transition matrices are composed of the scalar functions $s_i(\mathbf{y}(t))$ and $p_i(\mathbf{y}(t))$, taking values on the interval $[0, 1]$, and denoting the proportion of the individuals in stage i at time t that respectively: survive the time period $(t, t+1]$, and move into the next stage at time $t+1$. Note that the number of individuals in stage i at time t that remain in stage i at time $t+1$ is given by $(1 - p_i(\mathbf{y}(t)))$. Define $n \times n$ matrices $S(\mathbf{y}(t))$ and $P(\mathbf{y}(t))$ as follows (note $(S)_{ij}$ denotes the ijth element of S; etc.)

$$\begin{aligned} (S)_{ii}(\mathbf{y}(t)) &= s_i(\mathbf{y}(t)) & i &= 1, \ldots, n; \\ (S)_{ij}(\mathbf{y}(t)) &= 0 & i \neq j,\ i, j &= 1, \ldots, n, \end{aligned} \tag{3}$$

and

$$\begin{aligned} (P)_{ii}(\mathbf{y}(t)) &= (1 - p_i(\mathbf{y}(t))) & i &= 1, \ldots, n; \\ (P)_{i+1\,i}(\mathbf{y}(t)) &= p_i(\mathbf{y}(t)) & i &= 1, \ldots, n-1; \\ (P)_{ij}(\mathbf{y}(t)) &= 0 & j \neq i, i+1,\ i, j &= 1, \ldots, n, \end{aligned} \tag{4}$$

where $p_n = 0$. Define an input vector $\mathbf{q}(\mathbf{y}(t)) = (q_1(\mathbf{y}(t)), \ldots, q_n(\mathbf{y}(t)))'$, where $q_i(\mathbf{y}(t))$ is a scalar function representing the number of individuals entering the ith growth stage during time period t from sources outside the population, including births. In stand growth models, q_1 is defined as the number of individuals entering the smallest growth stage through natural regeneration, and $q_i = 0$, $i = 2, \ldots, n$.

The survival and transition matrices, the regeneration vector, and the state and control vectors are combined into the following difference equations for a population with an initial state $\mathbf{x}(0)$ that is harvested immediately with the control $\mathbf{u}(0)$:

$$\begin{aligned} \mathbf{x}(1) &= \mathbf{x}(0) - \mathbf{u}(0) \\ \mathbf{x}(t+1) &= \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)) \qquad t = 1, 2, \ldots, \end{aligned} \tag{5}$$

where the growth vector $\mathbf{f}$ has the explicit form,

$$\mathbf{f}(\mathbf{x}(t), \mathbf{u}(t)) = P(\mathbf{y}(t)) S(\mathbf{y}(t)) \mathbf{x}(t) + \mathbf{q}(\mathbf{y}(t)) - \mathbf{u}(t). \tag{6}$$

For stand growth and yield projection, the state variable represents the distribution of trees by diameter class. The first application of this framework (Usher, 1969) involved a matrix model with fixed parameters for the proportions of trees that moved between diameter classes. Later applications extended the model to include size specific harvesting rates (e.g., Rorres (1978)), density–dependent equations for regeneration, growth and survival (e.g., Adams and Ek (1974)), and multiple species (e.g., Solomon et al. (1986)). An important feature of stage–structured models is their tractability for management analysis (Adams and Ek, 1974; Haight et al., 1985; Haight, 1987). Stage–structured models can be constructed with equations from single–tree simulators with only a small loss of projection detail (see Haight and Getz (1987a)).

The problem of exploiting a general renewable resource can be formalized as follows. Define $R(\mathbf{x}(t), \mathbf{u}(t))$ as the revenue obtained at the end of time period t, where the resource is in state $\mathbf{x}(t)$ at the beginning of this time period and the harvest control $\mathbf{u}(t)$ takes place at the end of the time period. Let δ denote a discount factor related to the real discount (interest) rate r by $\delta = 1/(1+r)$. The infinite time horizon resource management problem can now be defined as:

$$\max_{\{\mathbf{u}(0), \mathbf{u}(1), \mathbf{u}(2), \ldots\}} J(\mathbf{x}(0)) = \sum_{t=0}^{\infty} \delta^t R(\mathbf{x}(t), \mathbf{u}(t)) \tag{7}$$

subject to the growth equations (5) and initial resource state $\mathbf{x}(0)$. Suppose this problem has a solution denoted by $\mathbf{u}^\star(t)$, $t = 0, 1, \ldots$, with corresponding state $\mathbf{x}^\star(t)$, $t = 1, 2, \ldots$, and present value $J^\star(\mathbf{x}(0))$. Since it is impossible to numerically solve an infinite time horizon optimal control problem, for computational purposes a related finite time horizon problem must be formulated. The infinite time horizon problem can be approximated by a finite time horizon problem that includes a transition period with length T and a terminal state $\mathbf{x}(T)$. If the terminal state is free and no cost is attached to leaving the resource in any particular state, the resource system is often heavily exploited in the time intervals leading up to and including T. Noting that the free terminal condition did not affect the optimal solution to the initial period harvest level $\mathbf{u}^\star(0)$ for large T, Haight (1985) avoided this problem with a sequential solution algorithm that repeatedly solved for and implemented the first period harvest control.

An alternative finite time horizon problem formulation involves constraining the resource system to be in equilibrium at the beginning of time period T; that is, $\mathbf{x}(t+1) = \mathbf{x}(t) = \mathbf{x}$, say, for $t = T, T+1, \ldots$. From growth equation (5) and the equilibrium constraint, it follows that

$$\mathbf{x} = \mathbf{f}(\mathbf{x}, \mathbf{u}). \tag{8}$$

Let $\mathbf{x_u}$ denote a solution to equation (5) for a given $\mathbf{u} \in U^e$ defined by

$$U^e = \{\mathbf{u} \in U \mid (\mathbf{x_u}, \mathbf{u}) \text{ is a biologically feasible solution to (8)}\}. \tag{9}$$

The equilibrium endpoint problem is defined as

$$\max_{\{\mathbf{u}(t),\ t=0,1,\ldots,T-1\}} J_T(\mathbf{x}(0)) = \sum_{t=0}^{T-1} \delta^t R(\mathbf{x}(t), \mathbf{u}(t)) + \frac{\delta^T}{1-\delta} R(\mathbf{x_u}, \mathbf{u}) \tag{10}$$

where $\mathbf{x_u} = \mathbf{x}(T)$ and $\mathbf{u} \in U^e$. Note that the second term on the right side corresponds to $\sum_{t=T}^{\infty} \delta^t R(\mathbf{x_u}, \mathbf{u})$. The idea here is to maximize $J_T(\mathbf{x}(0))$ for initial stand condition $\mathbf{x}(0)$ subject to the growth dynamics (5) holding for $t = 0, 1, \ldots, T-1$ and the pair $(\mathbf{x_u}, \mathbf{u})$ satisfying equilibrium equation (8). If $J_T^\star(\mathbf{x}(0))$ is the value corresponding to the optimal solution to the T–horizon equilibrium endpoint problem, then $J_T^\star(\mathbf{x}(0))$ approximates $J^\star(\mathbf{x}(0))$, the value of the infinite time horizon problem, and converges to it as $T \to \infty$. The difference between $J_T^\star(\mathbf{x}(0))$ and $J^\star(\mathbf{x}(0))$ can be regarded as the cost associated with the constraint that the system must be in equilibrium for $t \geq T$. It is worth noting that the optimal equilibrium pair $(\mathbf{x_u}, \mathbf{u})$ depends on $\mathbf{x}(0)$, T, and δ.

The infinite time horizon problem (7) can also be approximated by a finite time horizon problem in which the terminal endpoint is constrained to be a fixed equilibrium endpoint. One choice for the fixed endpoint is the extremal steady state associated with the infinite time horizon problem (7). Optimal solutions to infinite time horizon harvesting problems often converge asymptotically to an extremal steady state solution pair denoted by $(\mathbf{x}_\delta, \mathbf{u}_\delta)$ that depends on the discount factor δ and satisfies equilibrium condition (8) and a set of necessary conditions derived from Pontryagin's Maximum Principle (see for example Horwood and Whittle (1986)). With an extremal steady state target, the fixed endpoint problem is

$$\max_{\{\mathbf{u}(t),\ t=0,1,\ldots,T-1\}} I_T(\mathbf{x}(0)) = \sum_{t=0}^{T-1} \delta^t R(\mathbf{x}(t),\mathbf{u}(t)) + \frac{\delta^T}{1-\delta} R(\mathbf{x}_\delta,\mathbf{u}_\delta) \tag{11}$$

subject to the growth dynamics (5) holding for $t = 0, 1, \ldots, T-1$ and the endpoint constraint $\mathbf{x}(T) = \mathbf{x}_\delta$. If $I_T^\star(\mathbf{x}(0))$ is the value corresponding to the optimal solution to the T–horizon fixed endpoint problem, then $I_T^\star(\mathbf{x}(0))$ approximates $J^\star(\mathbf{x}(0))$, the value of the infinite time horizon problem, and approaches it as $T \to \infty$. The additional constraints on $\mathbf{x}(T)$ mean that $I_T^\star(\mathbf{x}(0))$ is less than or equal to $J_T^\star(\mathbf{x}(0))$ for any finite T. Associated with the fixed endpoint problem is the question of reachability of the target set (i.e., do any controls exist that drive the system to the specified endpoint $\mathbf{x}(T)$ in the allocated time interval T).

A second choice for the fixed endpoint is an "investment efficient" steady state that satisfies a marginal value growth percent criterion (Adams, 1976) that is equivalent to the criterion used to determine rotation ages for even–aged stands (Chang, 1981). Most authors choose investment efficient steady states as targets in uneven–aged management (Adams, 1976; Buongiorno and Michie, 1980; Martin, 1982). It turns out that an investment efficient steady state satisfies a slightly different set of necessary conditions than those that are satisfied by an extremal steady state (Haight, 1985). Thus, for sufficiently large T, the solution to problem (11) with an investment efficient steady state endpoint has a lower present value relative to the present value of a solution that is constrained to achieve an extremal steady state.

A third choice for the fixed endpoint is the steady state that maximizes managed forest value. Managed forest value measures the present value of an infinite series of steady state harvests (Rideout, 1985). In the context of problem (10), managed forest value is $\frac{\delta}{1-\delta}R(\mathbf{x}_\mathbf{u},\mathbf{u})$, the present value at time T of the steady state pair $(\mathbf{x}_\mathbf{u},\mathbf{u})$. Steady states that maximize managed forest value are called maximum sustainable rent solutions, and they are independent of the discount factor. Maximum sustainable rent steady states are the same as the extremal steady state only in the special case where $\delta = 1$ (Haight and Getz, 1987b). Thus, for sufficiently large T, management regimes that are constrained to achieve a steady state that maximizes managed forest value are suboptimal relative to solutions that are constrained to achieve an extremal steady state.

PENALTY FUNCTION METHODS

The costs of the fixed and equilibrium endpoint constraints can be estimated by solving problems (10) and (11) for increasing transition period lengths. These problems have been solved using gradient projection methods (Adams and Ek, 1974) and linear programming (Michie, 1985), but computational limitations prevented the authors from solving problems with three or more transition harvests. The methods discussed below can be used with linear or nonlinear stage-structured models, and problems with three or more transition harvests are easily solved. The solution method involves converting the fixed and equilibrium endpoint problems, which have terminal steady state constraints, into equivalent unconstrained problems with free terminal points.

In the context of problem (10), an optimal sequence of harvests $\mathbf{u}^*(t)$, $t = 0, 1, \ldots, T-1$, is sought subject to the growth dynamics (5) and the terminal stand structure $\mathbf{x_u}$ satisfying the equilibrium condition (8). From equilibrium constraint (8) and growth dynamics (6), it follows that the steady state harvest vector $\mathbf{u} = \mathbf{h}(\mathbf{x_u})$ satisfies

$$\mathbf{h}(\mathbf{x_u}) = P(\mathbf{y})S(\mathbf{y})\mathbf{x_u} + \mathbf{q}(\mathbf{y}) - \mathbf{x_u}, \tag{12}$$

and $\mathbf{h}(\mathbf{x_u}) \geq \mathbf{0}$. To ensure that the latter constraint is satisfied, let $\mathbf{g}(\mathbf{x_u})$ be the penalty vector containing elements g_i, $i = 1, 2, \ldots, n$, that are scalar functions defined by

$$g_i(\mathbf{x_u}) = \begin{cases} 0 & \text{if} \quad h_i(\mathbf{x_u}) \geq 0 \\ h_i^2(\mathbf{x_u}) & \text{if} \quad h_i(\mathbf{x_u}) < 0. \end{cases} \tag{13}$$

Thus, when the steady state harvest level in stage i is nonnegative, the penalty function g_i is zero, and when the harvest level is negative, the penalty function equals the square of the harvest level. Note that g_i is a continuous, nonnegative function of the terminal state $\mathbf{x_u}$. The penalty function is added to the objective function (10) by selecting a suitable vector $\mu \in R^n$ of positive constants; that is, the augmented objective function becomes

$$\max_{\{\mathbf{u}(t),\ t=0,1,\ldots,T-1\}} J_T(\mathbf{x}(0)) = \sum_{t=0}^{T-1} \delta^t R(\mathbf{x}(t), \mathbf{u}(t)) + \frac{\delta^T}{1-\delta} R(\mathbf{x_u}, \mathbf{h}(\mathbf{x_u})) - \mu \mathbf{g}(\mathbf{x_u}). \tag{14}$$

Note that the terminal state $\mathbf{x_u}$ must also satisfy

$$\mathbf{x_u} = P(\mathbf{y}(T-1))S(\mathbf{y}(T-1))\mathbf{x}(T-1) + \mathbf{q}(\mathbf{y}(T-1)) - \mathbf{u}(T-1). \tag{15}$$

Thus the augmented problem (14) is solved for a given vector μ, subject to growth dynamics (5) holding for $t = 0, 1, \ldots, T-1$, and with the terminal state $\mathbf{x_u}$ free.

Fixed endpoint problems are solved by defining a penalty vector that penalizes the objective function whenever the desired terminal state is not reached. In the context of problem (11) an optimal sequence of harvests $\mathbf{u}^*(t)$ is sought over the time interval $t = 0, 1, \ldots, T-1$ subject to the growth dynamics (5) and the constraint that the terminal state $\mathbf{x}(T) = \mathbf{x}_\delta$, the extremal steady state. Let $\mathbf{g}(\mathbf{x}(T))$ be the penalty vector containing elements g_i, $i = 1, 2, \ldots, n$, that are scalar functions defined by

$$g_i = (x_i(T) - x_{i\delta})^2 \ . \tag{16}$$

Note that, whenever the terminal state $x_i(T)$ does not equal the desired state $x_{i\delta}$, the penalty function g_i is positive. The augmented objective function for the fixed endpoint problem is

$$\max_{\{\mathbf{u}(t),\ t=0,1,\ldots,T-1\}} I_T = \sum_{t=0}^{T-1} \delta^t R(\mathbf{x}(t),\mathbf{u}(t)) + \frac{\delta^T}{1-\delta} R(\mathbf{x}(T),\mathbf{u}(T)) - \mu \mathbf{g}(\mathbf{x}(T)), \quad (17)$$

where $\mu \in R^n$ is a vector of positive penalty function parameters. Since $\mathbf{x}(T)$ is a function of the state and control in period $T-1$, the augmented fixed endpoint problem (17) can be solved as a discrete time optimal control problem with a free terminal point.

For a given penalty function parameter μ, the auxilary problems (14) and (17) can be solved using gradient techniques (see Haight et al. (1985)). In general, it is possible to get arbitrarily close to the optimal solution to the original constrained problem by computing the solution to the auxilary problem for sufficiently large μ. However, for very large values for μ, more emphasis is placed on feasibility and the gradient solution method moves rapidly toward a feasible point. Typically a solution is reached that is far from optimal, but movement away from the point is difficult because of the size of the penalty function, and as a result, premature termination of the gradient method takes place. This problem is avoided by solving a sequence of problems for increasing penalty function parameters. With each new value for μ, the gradient method is employed starting with the optimal solution corresponding to the previous parameter problem. The solution to each problem is generally infeasible, but as μ is made large, the solutions approach the optimal solution to the original constrained problem.

The penalty function methods were applied to harvesting problems for stands that included mixtures of California white fir (*Abies concolor* (Gord. & Glend.) Lindl. (Iowiana [Gord.])) and red fir (*Abies magnifica* A. Murr.) (Haight and Getz, 1987b). A stage–structured model was constructed using equations from CACTOS, a single–tree simulator for California mixed conifer stands (Wensel and Koehler, 1985). Twenty–one state and control variables were defined for each species, and problems with up to thirteen transition harvests were solved on an IBM–PC microcomputer.

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FOREST MANAGEMENT INTENSITY/WOOD GROWING COSTS/FINANCIAL RETURNS

Ben Holtman*

ABSTRACT. Through simulation analysis of loblolly pine plantations, the following questions were examined.

- Does the addition of a treatment to a management regime, which adds up-front cost per acre, increase the cost per unit of wood produced?
- Do major changes in long-term expectations for raw material price and/or cost of capital typically imply that a change in the mix of treatments comprising a regime is appropriate?
- Or, stated differently, is the addition of a treatment typically a "matter of diminishing returns"; so that, as the long-term forestry investment climate becomes more (or less) favorable, the preferred management level is raised (or lowered) by adding (or dropping) treatments?

The following observations were made based on financial analysis of the simulation results.

- The addition of forestry treatments to a base management regime decreases wood growing costs per unit, even though the establishment and/or silvicultural costs per acre were increased.
- Also, the more intensive management level typically has a higher net present value and internal rate of return.
- Sensitivity analysis showed that a high level of management intensity ranks well against less intensive management regimes in terms of unit wood growing costs and financial returns over a wide range of future price expectations and discount rates.

INTRODUCTION

The underlying rationale for corporate investments in land and timber is widely recognized (5, 6, 7, 10, 12). In addition to conventional financial investment criteria, the special strategic nature of forestry investments for integrated wood processing firms is also emphasized. For these firms, the forestry investment insures a supply of stumpage at some future date for a predictable cost. In this industry, a company's capacity to excel is heavily influenced by the cost of its raw material. Estimates made by Clephane and Carroll (7) indicate that in 1981 delivered timber was 60-70 percent of the total production cost of lumber

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and plywood and 20-30 percent of the total production cost of white paper and linerboard. Thus, in addition to conventional financial goals, there is an additional objective to achieve a level of production which insures a desired level of raw material self-sufficiency.

Accepting the objective of tree-growing for these purposes, the question is asked: "What is the appropriate level of management intensity for softwood production?" In particular, should yield enhancing treatments such as site preparation, planting, hardwood control, thinning and nitrogen fertilization be done, or would a more extensive and lower cost per acre form of management be preferable? Attention will be restricted to the addition/deletion of an entire treatment. Treatment/cost optimization (e.g., fertilization dosage) is not considered here.

METHODOLOGY

A lower coastal plain clearcut site in Eastern North Carolina was selected to illustrate the financial results which might be expected as management intensity is increased. Four management levels for loblolly pine (P. taeda) were chosen for evaluation through simulation. These management levels, treatment cost and yield assumptions are given in Table 1. Stumpage price assumptions used are shown in Table 2. Using these stumpage prices and current tax law, net present values and internal rates of return were computed on an after-tax basis for a single rotation operating at each of the four management levels. The cost for the use of the land is included by budgeting for land purchase at the beginning of a rotation and resale at the end. Also computed was the wood growing cost. Referred to as cost - price by Lundgren (11), it is that after-tax stumpage value which would have to be charged to exactly recover forestry investments, including charges for the cost of all employed capital. Where there are multiple removals, thinnings plus clearcut, the stumpage value charge is the same for all. For simplicity this analysis was done in constant dollars (1985), so the interest rates and internal rates of return cited in the results are all on a real basis, net of inflation.

RESULTS

The wood growing costs for three discount rates are shown in Figure 1-A. As each additional treatment is added, the overall wood growing cost decreases. Therefore the incremental cost of the incremental wood produced was even lower. Note that decreasing the discount rate has the effect of decreasing the wood growing cost advantages for intensive management. Increasing the cost of capital, on the other hand, increases the incentive to apply a higher level of management intensity. This minimizes the holding period for the investment or produces a higher yield for the same period. Because the cost of growing wood is reduced by increasing management intensity, the financial returns are also improved. Figure 1-B shows that the internal rate of return is increased by increasing management intensity for all stumpage price future scenarios considered here. While the returns are not as attractive under the pessimistic price future, it is still best to manage intensively. Figure 2 indicates that the same is generally true for NPV under all

Management Level	Description	Treatment Cost ($/A)*				Yields (CCF/A)**				
						Thinning		Clearcut		
		Year 0	Year 4	Year 15	Year 23	Age	Pulpwood	Age	Pulpwood	Sawtimber
Thin Only	Chop, Burn, Plant, Accept 25% Hardwood BA, Thin to 65 ft^2/A at Age 18, Clearcut at 35. Achieve SI_{25}=55.	123				18	4.0	35	3.1	12.1
Thin + Hardwood Control	Chop, Burn, Plant, Reduce Hardwood Competition to 5% BA at Age 4. Thin to 65 ft^2/A at Age 18, Clearcut at 35. Achieve SI_{25}=55.	123	40			18	6.2	35	3.2	21.6
Thin + Intensive Site Prep	Intensive Site Prep to Raise SI_{25} from 55 to 76. Includes Drain, Shear, Pile, Bed, Phosphorus Bed Fertilization, Plant, Thin at Age 14 to 75 ft^2/A. Clearcut at 30.	261				14	8.1	30	3.6	31.9
Thin + Intensive Site Prep + N Fert.	Site Prep, Plant, and Thin as Above. Nitrogen Fertilization at Ages 15 and 23. Clearcut at 28.	261		44	44	14	8.1	28	3.6	31.9

* From Straka et al (13). Other costs included are period costs of $4/A/year and land purchase at time of establishment of $200/A. The land is resold at clearcut adding a positive cash flow of $200/A.

** Loblolly plantation yields from VPI growth models (3, 4). Site preparation response from Allen and Campbell (2),Gent et al (9), and Terry et al (14). Fertilization response from Allen et al (1).

Table 2. Pine Stumpage Value Assumptions*, 1985 $

	$/CCF**		
	Optimistic	Control	Pessimistic
Pulpwood	36	30	20
Sawtimber	159	111	63

discount rates and future stumpage price scenarios. There was one exception - the combination of the 8% real discount rate and DRI's pessimistic price forecast. Here there is a slight decline in 8% real NPV with the addition of the large investment in intensive site preparation.

In Figure 3 the effects of decreasing the role of land ownership costs are illustrated. Assigning 2% unique land value appreciation is equivalent to reducing the interest charged for land capital by 2%. As can be seen the effects are small.

DISCUSSION

A striking feature of these results is the consistency of ranking between wood growing cost, net present value and internal rate of return. The more intensive management ranks best by all criteria. This is interesting because wood cost does not recognize unique wood values, while the other measures do. Therefore, the dominance of the more intensive management is relatively insensitive to the value assumptions used. Management intensity which maximizes yield and financial return to the acre, also provides low growing cost per cunit.

In these examples, the addition of a treatment does not show a "diminishing returns"*** effect. Rather the rate of return is actually increasing as management intensity is increased. The internal rate of return curve is for the total management level. As long as it is rising, the incremental return for the incremental investment must be greater than the base to which the treatment was added. As this was not an exhaustive analysis of management alternatives, there are likely to be even higher levels of management intensity which further increase returns.

* Southwide Year 2000 Forecasts of Data Resources, Incorporated (8).

** Assumed clearcut stumpage realizations. Pulpwood from thinning was valued at $10/CCF less.

*** The reader should be aware that conventional technical economics usage of the phrase law of diminishing returns would exclude these examples. The strict definition of this phrase applies only where technology is held constant.

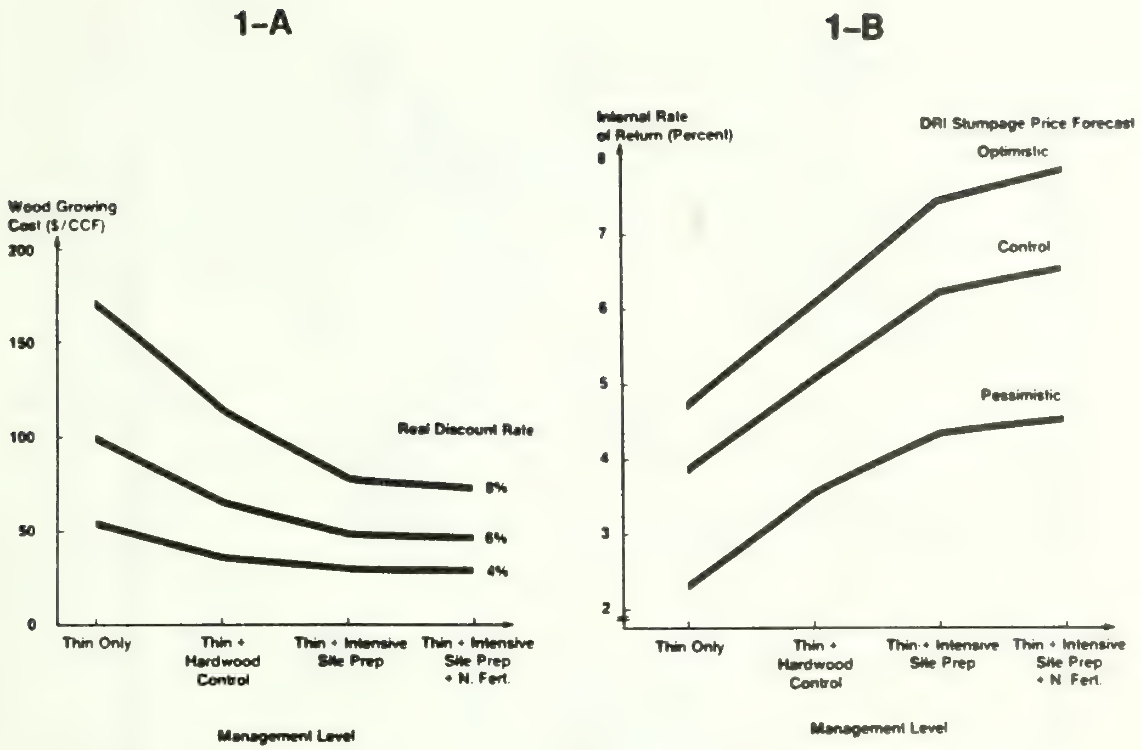

Figure 1. Financial Implications of Increasing Management Intensity

MANAGEMENT IMPLICATIONS/LOBLOLLY PINE

While the exceptions noted in this analysis deserve recognition and can play a role, in general, the long-term, single-acre strategic implications are that some form of intensive forest management is financially superior to extensive management. This appears to be a robust conclusion because it holds up over a wide range of value assumptions and financial criteria.

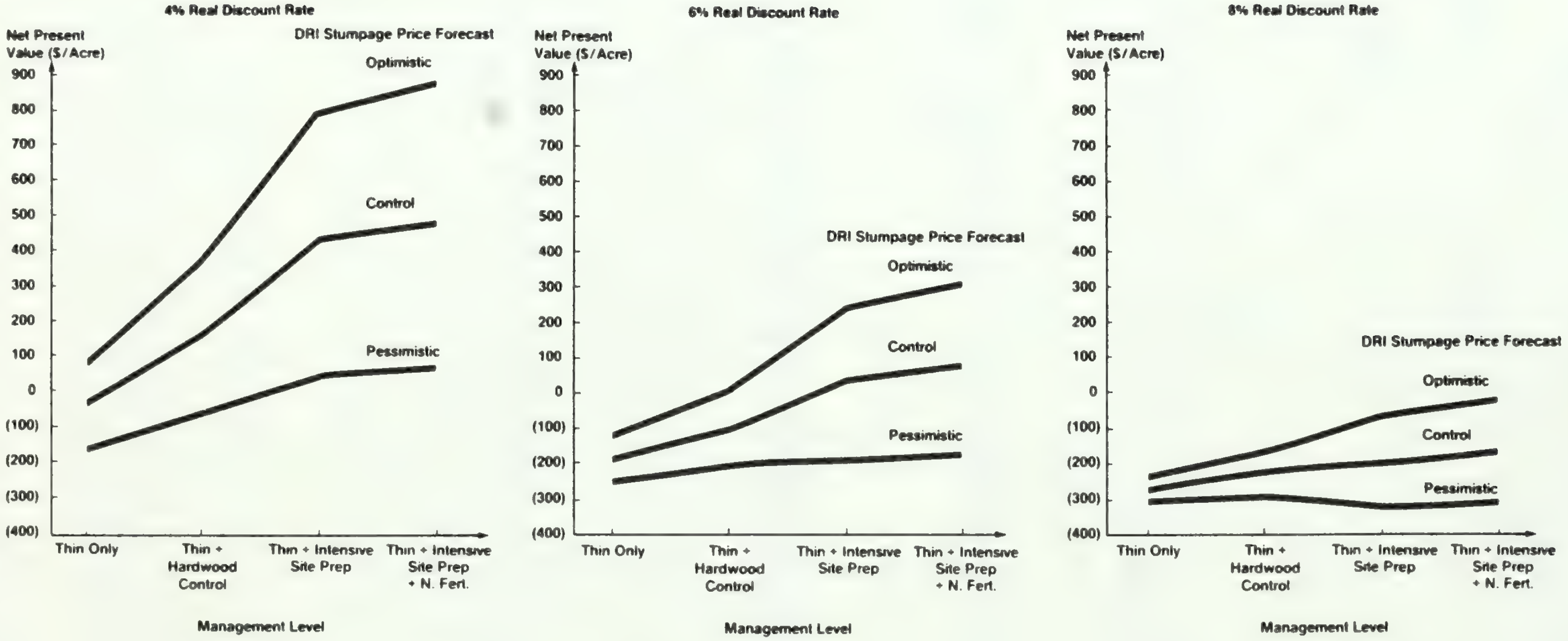

Figure 2. Financial Implications of Increasing Management Intensity – Net Present Value

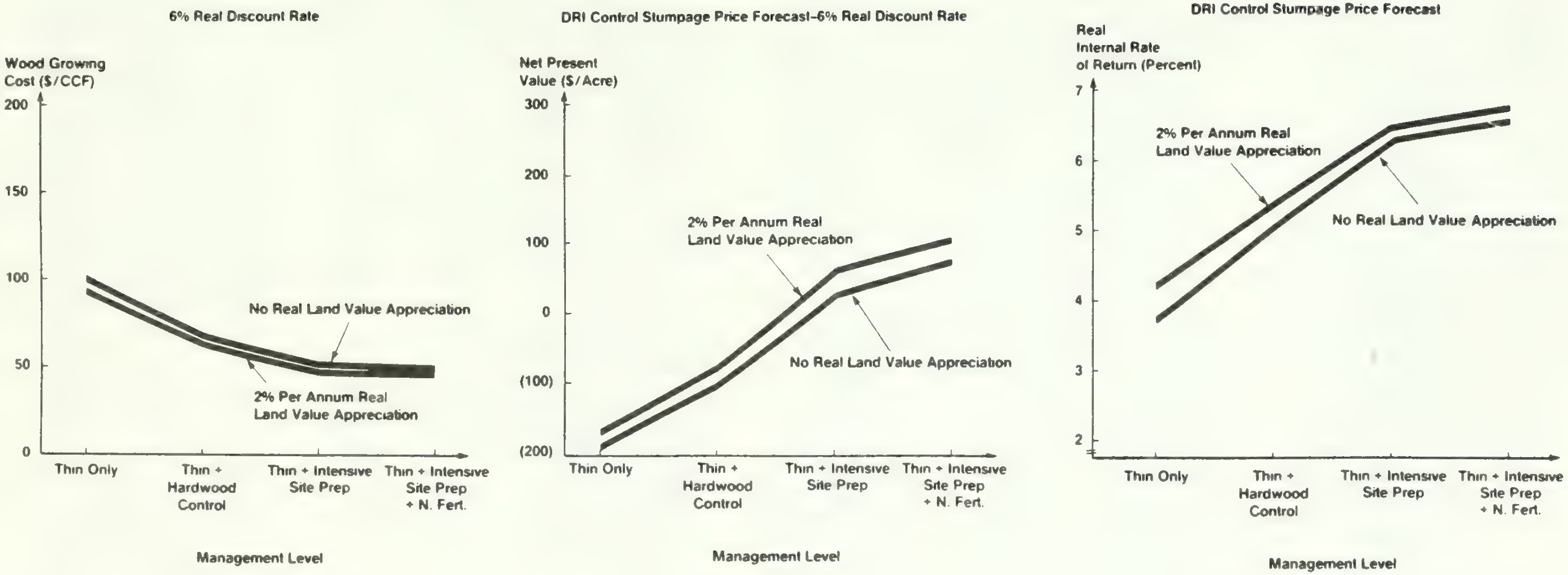

Figure 3. Effect of Unique Land Appreciation on Forest Management Intensity Financial Relationships

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The Rate of Return of Individual, Forest- Grown Black Walnut Trees

Carl W. Mize[1]

ABSTRACT: The real rate of return (ROR) was estimated for individual black walnut trees with initial DBHs from 6 to 30 inches, growth rates of 3, 6, and 12 rings per inch for 20 years, and many combinations of potential merchantable heights for prime and average veneer logs and sawlogs and curves of annual ROR versus DBH were prepared. The ROR of individual trees varied from 34% to 2%. The relation of ROR to DBH was different for the three growth rates. For a given DBH and growth rate, the grade of the butt log essentially determined the ROR.

INTRODUCTION

One of the tasks of most Iowa foresters is marking trees for thinning. Although black walnut (*Juglans nigra*) is generally not as abundant as many other tree species, individual walnut trees can be worth more than an acre of many species. Woodlot owners frequently ask foresters whether an individual walnut tree or a number of walnut trees should be harvested now or later. If the forester has the time, BLAWAP, the BLAck WAlnut Program (Gutierrez-Espeleta and Mize 1986) can be used to estimate the rate of return of specific trees which can be useful in deciding whether to harvest a tree now or later. But this requires that the forester collect certain data, return to the office, run the program, and then return to the woodlot to make recommendations. This often requires more time than the forester has available.

As a result, some Iowa foresters have asked if it would be possible to develop a set of tables, similar to the financial maturity studies of Guttenberg and Putnam (1951) and others, that would show the annual rate of return (ROR) of individual black walnuts over a wide range of conditions. This study was done to develop these tables.

METHODS

A computer program was written to estimate the initial value and the value in 20-years of about 6,300 hypothetical trees, each one representing a different combination of initial DBH, 20 year growth rate, and initial stem condition. The trees had initial DBHs of 6 to 30 inches by 2-inch intervals. Future DBH was not estimated by a growth model. Instead, fixed growth rates that represent high, medium, and low DBH growth were used. The DBH of each tree was increased 13.3, 6.7, or 3.3 inches to simulate a growth rate of 3, 6, and 12 rings per inch (RPI) for 20 years, respectively. For each DBH and growth rate combination, 139 combinations of potential merchantable height[2] for prime and average veneer logs and sawlogs were examined. The potential merchantable height could be 0, 8, 12, 16, 20, or 24 feet for a prime veneer log[3]. The potential merchantable

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[2] Potential merchantable height is the maximum length of a stem that can be used for a product given an increase in diameter and no change in stem characteristics, such as clearness and straightness.

[3] A prime veneer log must be at least 8 feet long, plus trim, and have a minimum small end diameter of 14 inches. It must be sound, straight, free of cracks and shake.

height for an average veneer log[4] could be 0, 6, 12, 16, 20, 24, or 32 feet above the end of the potential prime veneer log. The potential height of a sawlog[5] could be 0, 6, 8, 12, 16, 24, 32, or 48 feet above the end of the potential average veneer log. The maximum allowable sum of the potential prime veneer and average veneer merchantable heights was 32 feet, and the maximum allowable sum of the three potential merchantable heights was 48 feet. For example, a stem could have the first 8 feet as possible prime veneer, with 12 feet of possible average veneer above that and with another 24 feet of possible sawtimber above the potential average veneer log.

Value of each tree was determined by first estimating the board foot volume (Doyle) of each log class in its stem. The Doyle Log Rule was used because most black walnut are bought and sold by logs using the Doyle Rule. Volume was estimated by using a section of the BLAWAP program that simulates bucking a stem into logs with the objective of putting the maximum volume in prime veneer, followed by average veneer, and then saw timber. The estimated volume of a tree after 20 years of growth could be much larger and composed of higher-class logs than the initial volume of the tree, depending upon the potential merchantability of the stem. The volume for each log grade was multiplied by its value per board foot. For each log grade, value per board foot varied by diameter and length and was estimated through discussions with managers of black walnut veneer manufacturing plants (Figure 1). Trees that did not yield at least a 6-foot sawlog were treated as if they were being sold as firewood stumpage. Their value was calculated by assuming a cubic foot volume equal 0.42*BA*HT, where BA = basal area in square feet and HT = total height in feet (Gevorkiantz and Olsen 1955), 0.01093 split cords per cubic foot (Mize et al. 1982), and a stumpage value of $17.50 per split cord (Paul Wray, Forestry Extension, Iowa State University 1987, personal communication).

The part of the program that simulated bucking a stem utilized a taper function that uses the DBH and total height of a tree to estimate the diameter of the tree at a given height or the height of the tree at a given diameter. The DBH of each hypothetical tree was given, but to estimate its total height, an equation was developed from data collected across Iowa. Ninety four walnut trees were measured for DBH and total height. The oak site index (base age = 50) of the site where each tree was growing was estimated from soil maps and personal experience.

The equation developed from the height-DBH data (presented in the RESULTS) included site index as an independent variable. Therefore, it was necessary to assign a site index to each hypothetical tree. Because of the large differences in the growth rates (3, 6, and 12 RPI), I used a different site index for each growth rate. This allows the height-diameter relationship of the trees to reflect a site index that is representative of the quality of sites on which such a growth rate could be achieved. Site indices of 80, 65, and 50 (base age = 50) were used as representative of the growth rates of 3, 6, and 12 (RPI), respectively.

For each tree, its real ROR, excluding inflationary and deflationary effects and assuming no extra management costs, was calculated by using the following formula, $(V_f/V_p)^{0.05}-1$, where V_f = value in 20 years and V_p = initial value.

For logs 8 to 10 feet long, it must be 100% clear. Longer logs must have at least three clear faces and the fourth face must be at least 85% clear.

[4] An average veneer log must be at least 6 feet long, plus trim, and have a minimum small end diameter of 12 inches. Logs that are 6 feet long must be 100% clear. Longer logs must have at least two clear faces, with the other faces having sound defects only.

[5] A sawlog must be at least 6 feet long, plus trim, and have a minimum small end diameter of 11 inches. Logs should have two clear adjacent faces and be reasonably straight.

Figure 1. Stumpage rates in dollars per board foot (Doyle) used for value estimation.

Small end Diameter (in.)	Prime Veneer Length (ft.) 8	10	≥12	Sawlog Length (ft.) 6	≥8
10				0.15	0.30
11				0.15	0.30
12				0.30	0.50
13				0.30	0.50
14	0.90	1.20	1.30	0.50	0.50
15	1.20	1.50	1.60	0.50	0.50
16	1.80	1.90	2.10	0.50	0.50
17	1.90	2.00	2.20	0.50	0.50
18	2.10	2.40	2.60	0.50	0.50
19	2.10	2.90	3.00	0.50	0.50
>20	2.10	3.70	3.70	0.50	0.80

Small end Diameter (in.)	Average Veneer Log Length (ft.) 6	8	10	≥12
12	0.40	0.50	0.60	0.60
13	0.40	0.50	0.60	0.60
14	0.60	0.70	1.00	1.00
15	0.80	1.00	1.20	1.30
16	1.00	1.40	1.50	1.70
17	1.10	1.50	1.60	1.80
18	1.30	1.70	1.90	2.10
19	1.30	1.70	2.30	2.40
≥20	1.30	1.70	3.00	3.00

RESULTS

Meyer's model (1940) for predicting total height from DBH fit the height-DBH data well. The residuals, however, were related to the estimated oak site index, so the model was modified, which produced the following equation.

$$\text{Total height (ft.)} = 1.30 * (\text{Estimated Site Index}) * (1 - e^{(-0.1148 * \text{DBH})})$$

where Estimated Site Index is at base age 50 and
DBH is in inches

$n = 94$ $S_{yx} = 13.0$

A number of graphs of ROR versus initial diameter were made to examine the relationship of ROR to merchantable height. For all three growth rates, the same basic relationship of merchantable height to ROR was seen. The ROR was very strongly controlled by the quality of the butt log and only slightly by the length of the butt log and the presence of other, lower-quality logs above it. Only stems with an average veneer log as the butt log showed much of an effect of log length on ROR.

Three sets of curves, one for each growth rate, were prepared to show the relationship of ROR to initial DBH (Figures 2, 3, and 4). Each figure contains four lines, each one representing a different type of tree. The line labelled PRIME VENEER represents trees for which at least the first 8 feet of the stem have the characteristics of a prime veneer log. The AVG. VEN. (>6') line represents trees for which at least the first 8 feet of the stem have the characteristics of an average veneer log but not a prime veneer log. The AVG. VEN. (=6') line represents trees for which only the first 6 feet of the stem can produce an average veneer log. The ALL SAWLOGS line represents trees that can produce at least an 8 foot sawlog but no logs of a higher grade, no matter how large the tree might be. To develop the curve for each growth rate, the trees were separated into the four butt log classes just described , and the average ROR was calculated for each DBH class. The averages used showed clear trends but were fairly noisy, so they were smoothed by using the average of three consecutive DBH classes. This resulted in fairly smooth curves, and so the smoothed averages and values that were visually extrapolated for the 6-and 30-inch classes were plotted and connected to form the three figures.

Although each hypothetical tree was assigned a site index (for height estimation) that was considered representative for its growth rate, a specific growth rate can be achieved on a range of sites. A test was conducted to examine the effect of changing site index on the ROR. Changing the site index for all trees by 10 feet had almost no effect on the average ROR. The average change in ROR was 0.6, -0.2, and -0.3% for growth rates of 3, 6, and 12 (RPI), respectively. Also, 61, 66, and 85% of the trees had a change in ROR of less than 1% for 3, 6, and 12 RPI. Thus, ROR appears to be dependent upon the growth rate of a tree but upon not the site index of the site on which it grows.

DISCUSSION

During the study, I realized that putting the maximum volume in a prime veneer log, followed by an average veneer log and then a sawlog did not necessarily result in the maximum value. Because of the relationship of value to diameter and length (Figure 1), a stem could produce a long, small-diameter log that would have a larger volume but a lower value than a somewhat shorter log with a larger diameter from the same stem. This could be a problem in estimating the actual value of a stem, but the error in estimation should be about the same for the initial value and value after 20 years of growth. As a result, the ROR should not be affected very much.

If foresters have a minimum ROR to use as a guideline for determining when trees should be harvested, they should find Figures 2, 3, and 4 useful in deciding when to harvest individual black walnut trees in Iowa and probably in adjacent states. The curves should be used as an "estimate" of the ROR of an individual tree. As an "estimate," it is subject to error, and although ROR is presented as a point, the actual ROR probably will fall in an interval that extends about 1 to 2% above and below the point. Also, the ROR for trees with initial DBHs below 14 inches reflects their initial value as firewood, which is subject to considerable variation. Thus, the ROR of small trees could vary substantially depending upon local markets. The ROR of all trees with DBHs of 14 inches and larger is based upon their producing at least a sawlog initially. The ROR of these trees probably is subject to less local variation than that of the smaller trees. Undoubtedly the stumpage rate for veneer logs and sawlogs will vary from place to place and over time, but if the relative value of logs of different sizes and classes remains about the same as the values in Figure 1, the ROR of the larger trees should remain close to the values shown in the figures.

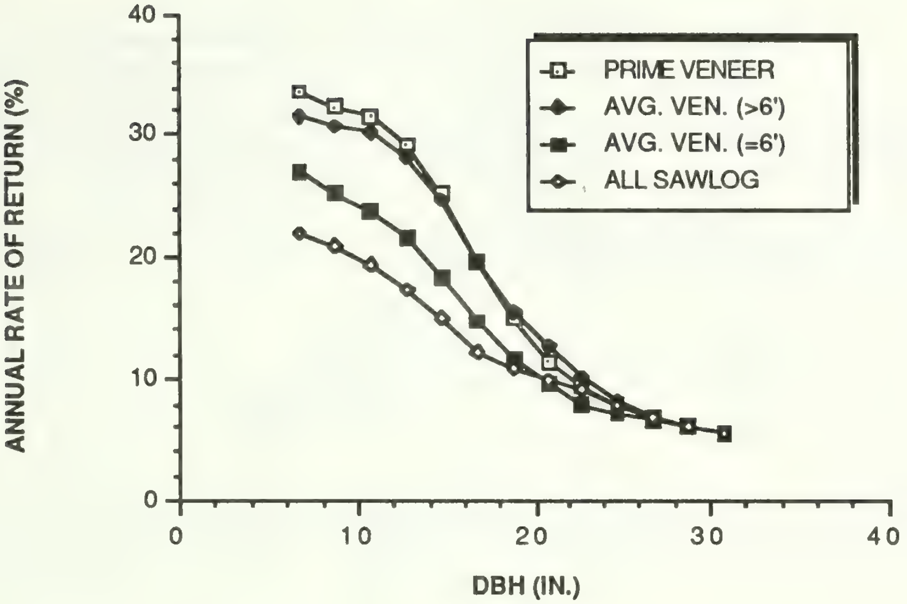

Figure 2. Annual rate of return for black walnut growing 3 rings per inch for 20 years. See text for description of the lines.

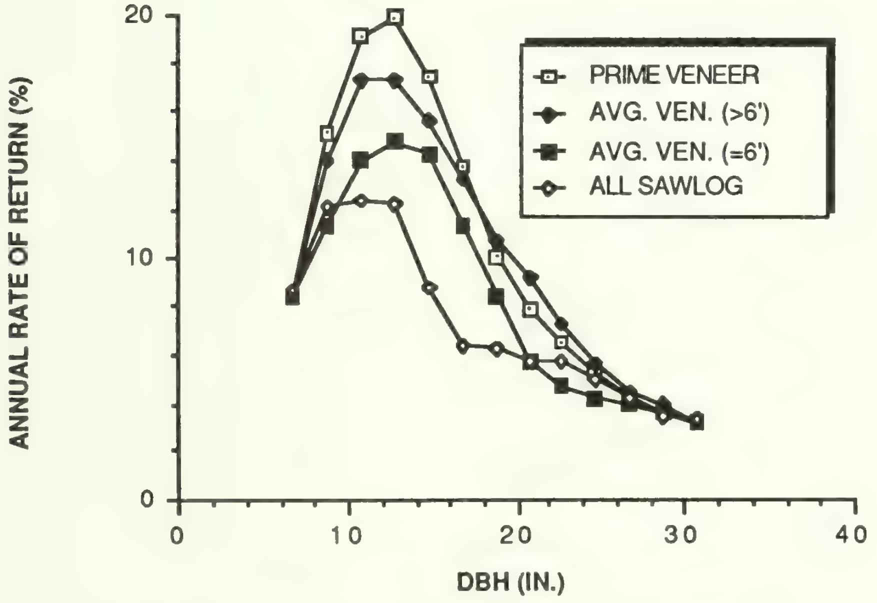

Figure 3. Annual rate of return for black walnut growing 6 rings per inch for 20 years. See text for description of the lines.

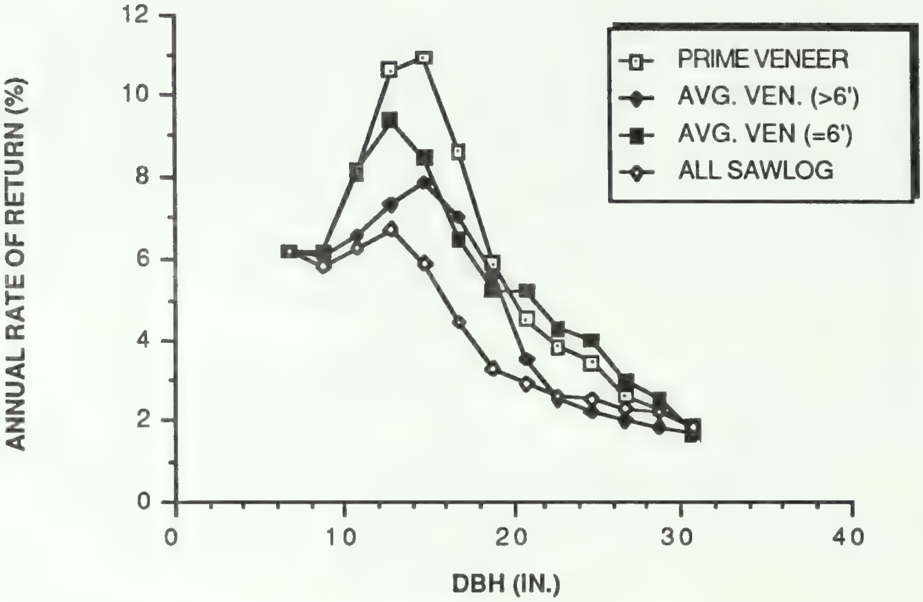

Figure 4. Annual rate of return of black walnut growing 12 rings per inch for 20 years. See text for description of the lines.

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A MULTIPLE-USE MANAGEMENT DECISION MODEL FOR *TAUNGYA* FARMING IN NIGERIA

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ABSTRACT. In multiple land-use management the amount of land or space allocated to competing uses on the same land is a major decision. Any forest manager involved in *taungya* practices must decide how many trees to plant per hectare and, thus, how much of land to allow the farmer to use. Based on results from an eleven-year-old plantation of *Terminalia superba*, a decision model is derived which includes space for agricultural crops, timber volume production, and average timber size. With a sensitivity analysis, results are presented for these three competing measures of production.

INTRODUCTION

Rainforest conversion has reached an alarming rate in Nigeria. Since it is the main source of timber production its efficient management has become a major concern. Increased demand on forest land for agriculture, urban development and timber production has made the problem of forest land management more complex. One major effort to lower the pressure to convert forest land to agricultural land has been the introduction of the *taungya* system of farming (Evans 1982). It is to encourage intensive forestry and agricultural practices on the same land during the first three years of the tree plantation's existence.

The area of land in tree plantations in Nigeria increased from 7000 ha in 1950 to 130,000 ha by 1977. Estimates by FAO (1981) indicates that there may now be about 300,000 ha of plantations of mainly exotic species of trees in Nigeria. Emphasis has shifted from silvicultural practices which rely on natural regeneration to plantation forestry in the past two decades. This trend has been encouraged by the fact that the methods which rely on natural regeneration result in slow growth ($<100m^3$/ha and $<2m^3$/ha/annum for exploitable volume production and annual increment, respectively).

However, plantation development is labour intensive and expensive when compared to traditional forestry management practices. Government policies are in favor of increased forest plantation development, using the *taungya* system. The alternative to this is to dereserve forest land for agricultural practices. This would not be in the interest of the forest manager. The *taungya* system is his best option. In Nigeria two types of this system are in operation. One is called *departmental*

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taungya. In the departmental *taungya* system, farmers are in the employment of the forest service. In the other type of *taungya* practice the farmers are not in the government employment. Whatever type of *taungya* system is involved the basic problem is the same--that of adopting the management option that will ensure the best mix of outputs (e.g. timber and various agricultural crops).

THE PROBLEM DEFINED

The forest manager involved in *taungya* practices must decide how many trees to plant per hectare and, thus, how much of growing space to allow for agricultural production. It is the problem of selecting, from among a set of proposed feasible management strategies, that strategy which is optimal. Such complex problems require the use of mathematical programming techniques.

We propose to use data from a spacing study in an eleven-year-old plantation of *Terminalia superba* to determine trade-offs between maximum timber production and space between trees to grow agricultural crops in the *taungya* system.

CHOICE OF AN APPROPRIATE MATHEMATICAL PROGRAMMING TECHNIQUE

In *taungya* practice the products are not usually measured in the same units. The wood products can be measured in volume or basal area per hectare while the agricultural products are usually measured in weights (tonnes). Therefore, the problem of selecting a strategy for management is not usually straightforward.

For such problems where incommensurable multiple outputs arise, Dress (1982) has discussed three possible approaches to the solution. The first approach is to form an objective function based on a subset of outputs which have same units of measurements and then use the other outputs as constraints. The second approach is to use proxy prices or values. Sometimes in economic terms it is referred to as opportunity cost. A third approach is to regard each of the expected outputs as subgoals and determine the management strategies that will optimize the trade-offs among subgoals.

The last approach is best suited for problems in the *taungya* system of management. A mathematical programming technique called Linear Goal Programming is best suited for such problem solutions. In this method of problem solution the objectives are translated into a set of specified goals. Then the economic form of linear programming is used to find a set of outputs which best minimizes deviations from the set goals. Other modifications of linear goal programming are ordinal-ranked or pre-emptive goal programs and linear parametric goal programming.

PROBLEM FORMULATION AND ANALYSIS

To ensure non-inferior strategies in the goal programming formulation it was necessary to set target levels at the optimum. In our case maximum diameter and maximum volume production were considered in turn, without consideration for the other. Although we were also interested in maximum growing space for agricultural crops this was inescapably tied up with the spacing for the tree crop.

The data consisted of diameter, survival and height measurements from an eleven-year-old *T. superba* plantation. Experimental treatments consisted of four spacings ranging from 1.83 by 1.83 m to 6.70 x 6.70 m. Each spacing was replicated four times in a 4x4 Latin square design. We tested and fitted response curve models with linear and quadratic terms for volume per hectare and mean diameter. Mean diameter (D) was related to growing space per tree where growing space is defined as

$$G = 10{,}000/T \ (m^2),$$

where T is number of trees per hectare. The final model was :

$$D = 11.217 + 0.5080G - 0.0059G^2 \qquad (1)$$

and it explained 81 percent of the variation in D for our data. With differential calculus, the maximum value of D was found to be 22.15 cm and it would be produced with a spacing of 6.56 by 6.56 m (232 trees/ha). The response model for total volume (V_t) as a function of (T) was of the form

$$V_t = 30.653 + .0606T - 0.000013T^2 \ (m^3/ha). \qquad (2)$$

Equation (2), which explains 65% of the variation in V_t for our data, was also analyzed to obtain maximum volume as in equation (1) above. A planting density of 2331 trees/ha (2.07 x 2.07 m spacing) will produce a maximum volume of 101.27m³/ha at age eleven.

Using the above results from the individual optimization solutions we established the following goals for the goal programming formulations:

Wood---G_1 = 101.27 m³/ha (Max) vol

Wood---G_2 = 22.15 cm (Max) diameter

Growing space for agricultural crops G_3 = decided from spacing that will achieve the first two goals.

To develop the model, it was assumed that a plan was needed for 100 hectares and that four planting spacings could be used:

X_i = area of land allocated to spacing i

$$X_1 + X_2 + X_3 + X_4 \leq 100 \text{ hectares}$$

Accounting rows are:

1. Wood maximum volume production --

   Minimize $VX_1 + VX_2 + VX_3 + VX_4 - Z_1 = 0$

2. Maximum diameter production --

   Minimize $DX_1 + DX_2 + DX_3 + DX_4 - Z_2 = 0$

Goal transfer rows:

1. Maximum volume production goal

   Minimize -- $Z_1 - d_1 = 10127.0$

2. Maximum diameter production goal

   Minimize -- $Z_2 - d_2 = 2215$

The linear programming formulation is:

Minimize $a = d_1^- + d_2^- + d_1^+ + d_2^+$

Subject to:

$$X_1 + X_2 + X_3 + X_4 \leqq 100$$

$$99.0X_1 + 87.48X_2 + 60.39X_3 + 40.81X_4 = 10127.0$$

$$12.45X_1 + 15.28X_2 + 19.01X_3 + 22.00X_4 = 2215.$$

The input data are described in Table 1.

TABLE 1. Input data for the linear goal programming solution.

$$\text{Min.}---X_1---X_2---X_3---X_4---+1.0X_5---+1.0X_6$$

Subject to:

(1) $1.00X_1 + 1.00X_2 + 1.00X_3 + 1.00X_4---X_5---X_6 \leqq 100.0$

(2) $99.0X_1 + 87.48X_2 + 60.39X_3 + 40.81X_4---+1.0X_5---X_6 \geqq 10127.0$

(3) $3.29X_1 + 7.70X_2 + 28.00X_3 + 63.0X_4---X_5---+1.0X_6 \geqq 15505$

The input data on table 1 were analyzed with a management science program (Quantitative System for Business, QSB). It is from a collection of management science decision support systems programs.

RESULTS

The initial tableau is presented in Table (2). This tableau is a result of several trial runs and the alteration of coefficients from the sensitivity analysis to obtain a reasonable feasible solution. An optimum solution was found after five iterations (Table 3). The results are summarized in Table 4.

The results indicate that all 100 hectares should be allocated to the X_4 planting spacing where an optimum of 60.46 m^3/ha and a diameter of $\frac{15251}{700} = 21.7$ cm would be obtained. The value of 15251 was divided by 700 beacuse during the search for optimum solution the coefficient for the diameter constraints was multiplied by 700. However, the information on opportunity cost was most useful (Table 5). If an optimum solution requiring the attainment of the set goals was strictly adhered to, there was less penalty for planting of the closer enspacement (X_1) than at wider enspacement.

DISCUSSION AND CONCLUSION

In summary, a global maximum was almost intractable but it did not preclude the existence of local maximum from the sensitivity test (Table 5); once the forest manager decides to plant at a wide spacing, the indication is that there would be a higher penalty for more hectares put under wider spacing if the achievement of an optimum volume production was still strongly in consideration. At the widest spacing only $(\frac{60.46}{101.27}) \cong 60\%$ of the optimum volume is achieved. However, it is also at the widest spacing that the optimum available growing space for agricultural crops occur.

The quantitative approach to solving problems in multiple use land management is a promising answer to the problem of fast deforestation in the tropics.

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TABLE 2. Initial tableau for the linear goal program.

		X1	X2	X3	X4	X5	X6	S1	A2	A3		B(i)
Basis	C(j)	0	0	0	0	1.000	1.000	0	M	M	B(i)	A(i,j)
SI	0	1.000	1.000	1.000	1.000	0	0	1.000	0	0	100.0	0
A2	M	99.00	87.48	60.39	40.81	1.000	0	0	1.000	0	10127	0
A3	M	3.290	7.700	28.00	63.00	0	1.000	0	0	1.000	15505	0
C(j)-Z(j)		0	0	0	0	1.000	1.000	0	0	0	0	
* Big M		0	0	0	0	0	0	0	1.000	1.000	25632	

TABLE 3. Final tableau (Total iteration = 5) for the linear goal program.

		X1	X2	X3	X4	X5	X6	S1	A2	A3		B(i)
Basis	C(j)	0	0	0	0	1.000	1.000	0	M	M	B(i)	A(i,j)
X4	0	1.000	1.000	1.000	1.000	0	0	1.000	0	0	100.0	0
X5	1.000	58.19	46.67	19.58	0	1.000	0	-40.8	1.000	0	6046	0
X6	1.000	-59.7	-55.3	-35.0	0	0	1.000	-63.0	0	1.000	9205	0
C(j)-Z(j)		1.520	8.630	15.42	0	0	0	103.8	-1.00	-1.00	15251	
* Big M		0	0	0	0	0	0	0	1.000	1.000	0	

(Min.) Optimal OBJ value - 15251

TABLE 4. Summarized results for the linear goal programming solution.

Variables		Solution	Opportunity Cost	Variables		Solution	Opportunity Cost
No.	Names			No.	Names		
1	X1	0.0000	1.5200	6	X6	9205.0000	0.0000
2	X2	0.0000	8.6300	7	S1	0.0000	103.8100
3	X3	0.0000	15.4200	8	A2	0.0000	-1.0000
4	X4	100.0000	0.0000	9	A3	0.0000	-1.0000
5	X5	6046.0000	0.0000				

Minimum value of the OBJ = 15251 Iters. = 5

TABLE 5. Sensitivity analysis results for the linear goal program.

C(j)	Min. C(j)	Original	Max. C(j)	C(j)	Min. C(j)	Original	Max. C(j)
C(1)	-1.5200	0.0000	+ Infinity	C(4)	- Infinity	0.0000	1.5200
C(2)	-8.6300	0.0000	+ Infinity	C(5)	-1.5437	1.0000	1.0261
C(3)	-15.4200	0.0000	+ Infinity	C(6)	0.9745	1.0000	+ Infinity

THE H/D RATIO IN MARITIME PINE (*PINUS PINASTER*) STANDS

Angelo M. Carvalho Oliveira[1]

ABSTRACT. The use of the h/d ratio in growth models and thinning practices for maritime pine stands in Portugal, as a first approach of its variation and maximum values, is presented. Sample plots of natural regenerated stands in Northern-central Portugal were used.

INTRODUCTION

The h/d ratio is widely used in Europe in order to quantify the risk of storm damage (wind and snow) and, in the thinning practice, to help with single tree classification. Its application on growth models (stand and tree level) for maritime pine implies the previous determination of its range of variation for the different tree classes as well as the establishment of a "maximum" value considering the risk of stand damage, mainly by wind.

MATERIALS AND METHODS

Fifty-seven inventory sample plots were set up in Northern-central Portugal, natural regenerated stands, measuring all trees of each plot and making its classification, separating two main classes (dominants - 100 largest per ha) and dominated (intermediate and suppressed trees with a subordinate position). This approach makes possible a first determination of h/d ratio variation (Table 1). Dead trees were not detected in this inventory.

Table 1. Estimated stand characteristics on the inventory sample plots.

	n	Mean	Maximum	Minimum	Standard Deviation
t	55	32.04	61	12	15.42
h_{dom} (meters)	51	16.10	28.80	16.10	5.01
dg (cm)	57	20.45	40.23	8.27	7.85
SDI	57	711.5	1014	488	103.54
H/D	57	64.33	80.10	50.96	6.54
h*/d*	57	91.89	132.60	64.80	12.58

t - age in years; h_{dom} top height in meters; d_g mean basal area tree diameter in cm; SDI "stand density index;" H/D represents the mean h/d ratio for all dominant trees of each plot; h*/d* represents the mean h/d ratio of all dominated trees in each inventory plot.

To take a closer look at h/d ratio variation with tree classes (kraft classification), site index, age, and density (measured as SDI) for three

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growth series (Marão, Cabreira and Serra D'Anta) were selected (Tables 2, 3 and 4).

Table 2. Growth series "Marão," plots 55, 57, 54, 53, 52, 51, 95 and 94.

Plots	t	h_{dom}	Site-index	d_g	SDI	H/D	h*/d*	hg/dg
55	50	26.5	24	35.27	736	70.8	87.4	73.99
57	48	21.2	20	27.2	498	66.0	107.7	79.05
54	45	18.2	18	21.5	568	76.2	90.4	81.7
53	45	18.2	18	25.49	717	61.1	80.3	70.68
52	45	15.4	16	19.75	673	65.4	98.6	75.29
51	45	21.1	20	28.63	721	88.2	72.0	71.87
95	40	15.3	16	21.07	638	59.9	96.7	74.48
94	32	16.2	18	19.59	610	64.2	91.9	79.69

h_g - plot arithemetic mean height in meters.
(1) Site index according Carvalho Oliveira (1985).

Table 3. Growth series "Cabreira," plots 17, 15, 13, 12 and 6.

Plots	t	h_{dom}	Site-index	d_g	SDI	H/D	h*/d*	hg/dg
17	30	19.6	22	35.3	732	64.6	81.6	73.19
15	15	9.4	18	11.1	702	56.6	78.2	66.39
13	38	21.5	22	29.7	815	57.1	85.4	66.34
12	38	19.6	20	21.1	654	64.9	94.4	75.06
6	31	17.3	19	20.6	638	65.8	84.8	72.57

Table 4. Growth series "Serra D'Anta," plots 27, 28, 30, 32.

Plots	t	h_{dom}	Site-index	d_g	SDI	H/D	h*/d*	hg/dg
27	14	10.8	20/22	12.6	781	56.3	90.0	79.04
28	14	9.8	18	11.9	778	62.2	81.3	77.85
30	14	9.8	18	8.3	488	73.9	108.5	95.03
32	13	8.0	18	8.9	685	64.1	93.1	81.58

RESULTS

Considering the h/d values for each tree and its class, and according to KRAFT classification, it is clear that the lower values of h/d are for the best types (kk1), Figure 1, which are also the thickest ones.

In even aged plots, growth series "Serra D'Anta," Figure 2, the h/d ratio increases with the top height, for the same diameter. No clear influence of SDI is detectable.

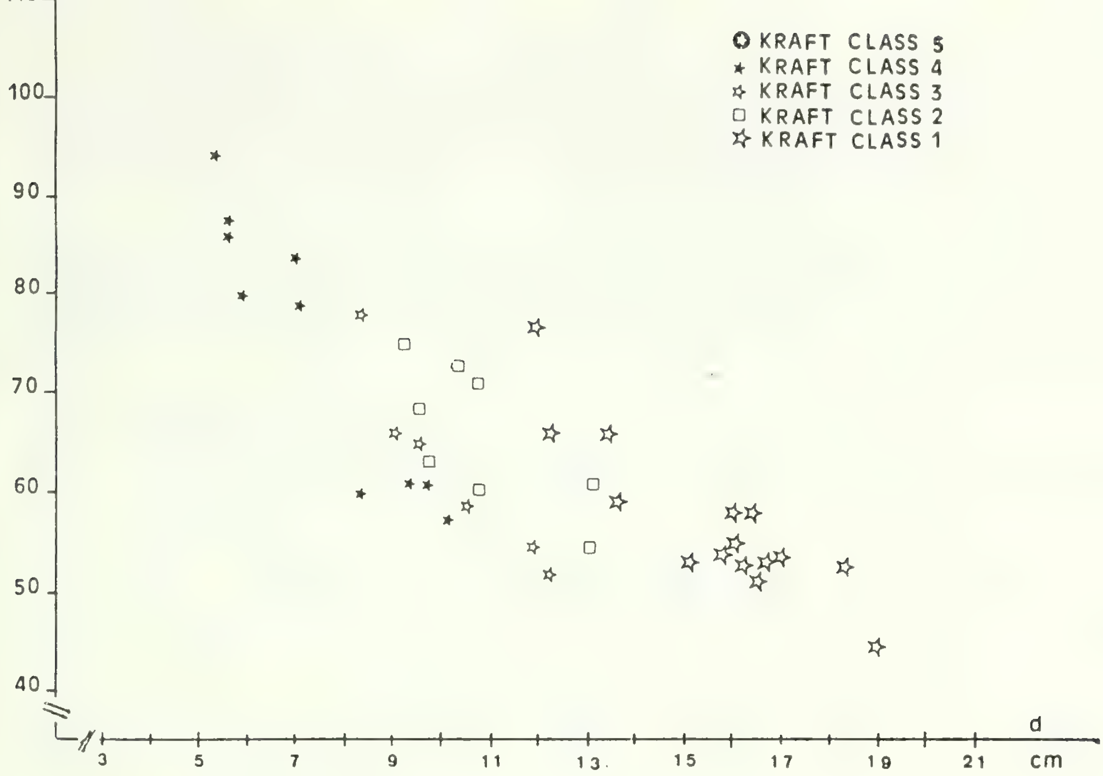


Fig. 1: h/d variation with tree class

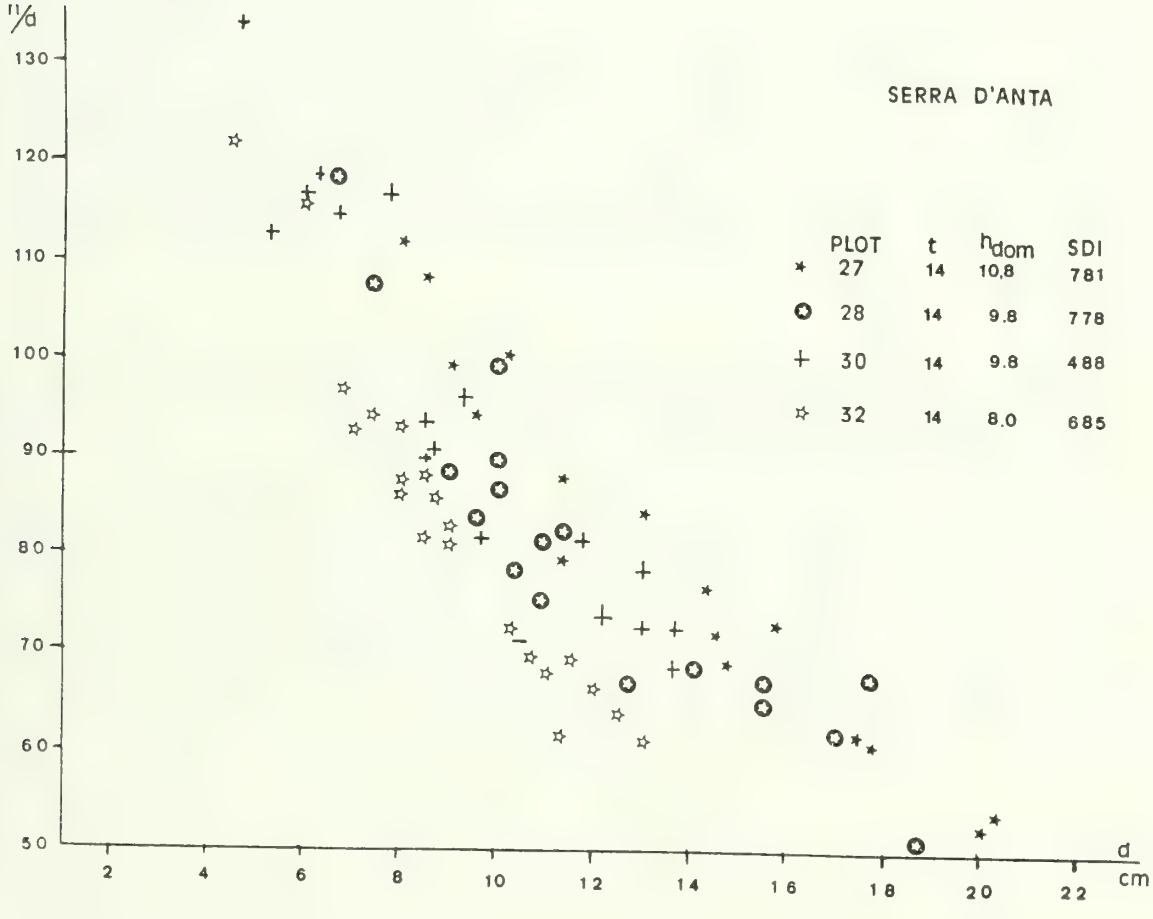


Fig. 2: h/d variation with diameter, growth serie "Serra D'Anta"

The growth series "Cabreira" confirms that, in general terms, h/d increases with site index, in plots with different ages (see Figure 3). Data of plot 15, the youngest one, also shows that the lower h/d ratio is certainly due to its poor site quality.

Figure 4, growth series "Marão," clearly shows the difference between plots 55 (site index 24), and plots 94, 95 and 52 (site index lower than 18). Here again, considering the same diameters, the h/d ratio increases with site index, is independent of age and seems to be independent of SDI.

As pointed out in the available literature, also in this case the relationship between h/d and d has the general form $h/d = b_0 + b_1 . \ln d$ or $\ln h/d = b_0 + b_1 . \ln d$. For example in Marao (Plot 52):

$$h/d = 250.386 - 59.096 \ln d$$

$R^2_{adj} = 0.901$; RMS = 17.657 ; Furnival Index 4.202

or

$$\ln h/d = 6.435 - 0{,}718 \ln d$$

$R^2_{adj} = 0.920$; RMS = 0.002 ; Furnival Index 3.324

where: ln refers to natural logarithms.

The mean H/D ratio for dominant trees, in growth series "Marão" (Figure 5) and "Cabreira" and "Serra D'Anta" (Figure 6), are presented for three significant levels (90%, 95% and 99%). It is clear that H/D ratio varies between 40 and 85 for a level of 99% precision in all growth series, independently of age, site index, density and mean diameter. If Serra D'Anta is ignored (that can be justified by the small number of dominant trees making $s_{\bar{x}} . t$ very large), we can say that H/D varies between 50 and 80 at the 95% significance level. If we look to the h*/d* ratio of the dominated trees in the 57 plots (Figure 7) its variation ranges from 75 to 105 in 80% of all measured trees.

CONCLUSIONS

As Kramer (1984) pointed out for Picea abies, to have maritime pine stands with the best stability against snow and wind, mean h/d values under 80 should be recommended.

According to Abetz (Kramer, 1984) trees with lower h/d ratio have bigger volume increment and show a bigger increment increase after thinning. Thus, it is desirable to use h/d ratios for single trees in order to help choose the best ones before thinning or pruning. We can further suggest, for single trees, values of the h/d ratio between 60 and 80 for the selection of the best ones. We must also remember the importance of h/d ratios when applying the "A value" of Johann (1982, 1983) in thinning practice and defining the concurrence status of single trees in growth models.

Fig.3: h/d variation with diameter, growth serie "Cabreira"

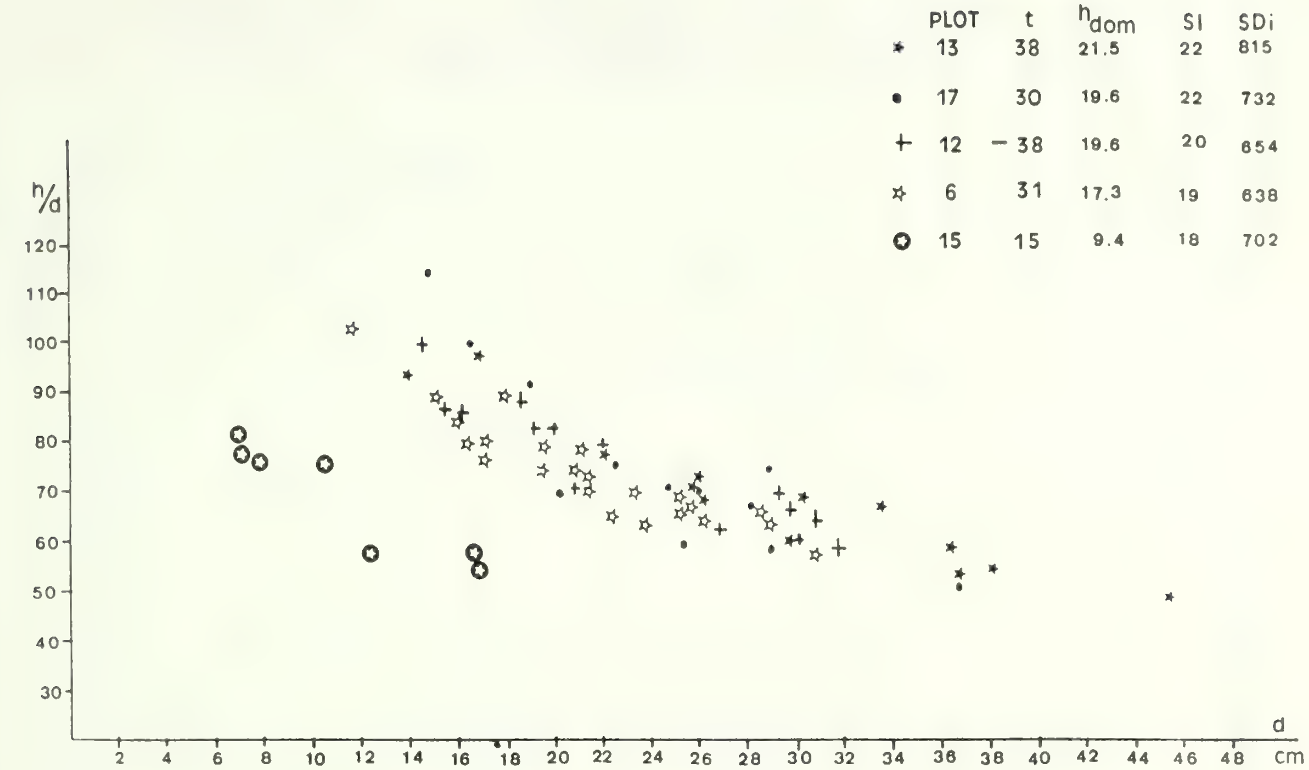


Fig.4: h/d variation with diameter, growth serie "Marão"

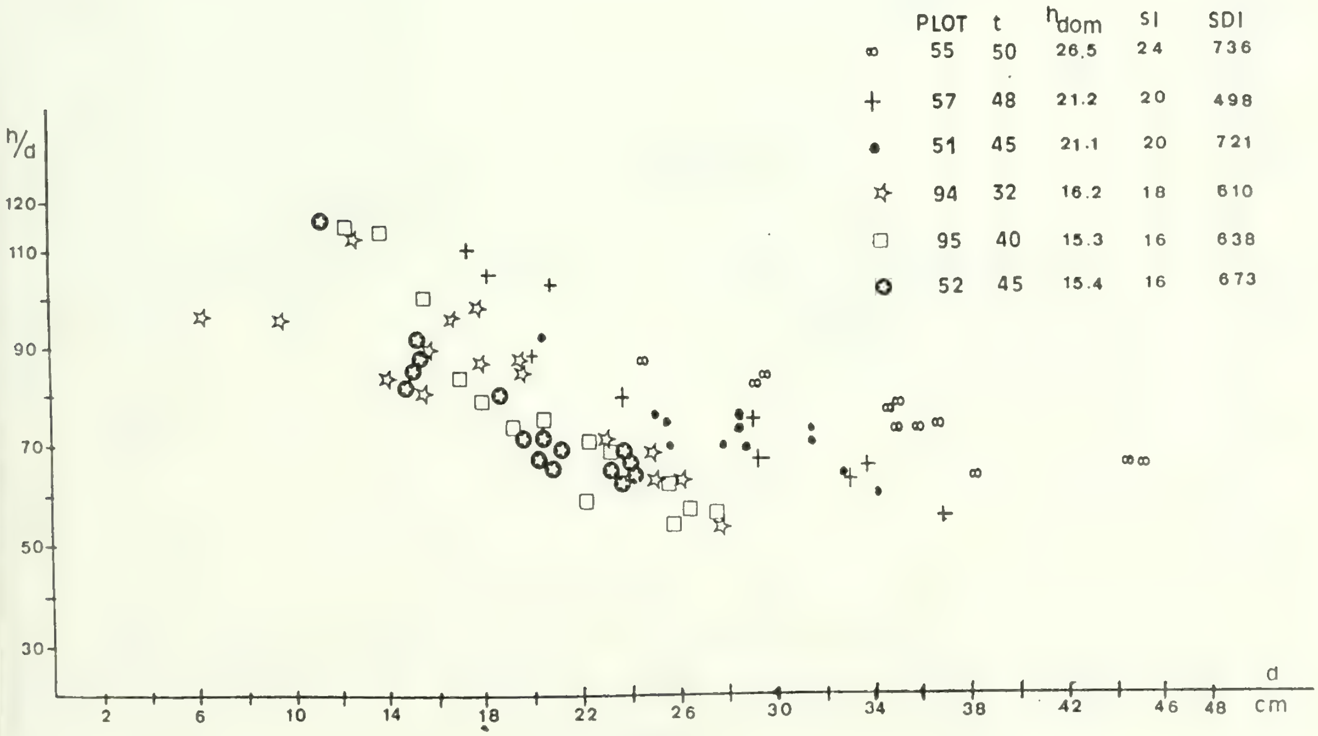


Fig. 5: The mean H/D ratio (dominant trees) in growth serie "Marão" for significance levels 90%, 95% and 99%.

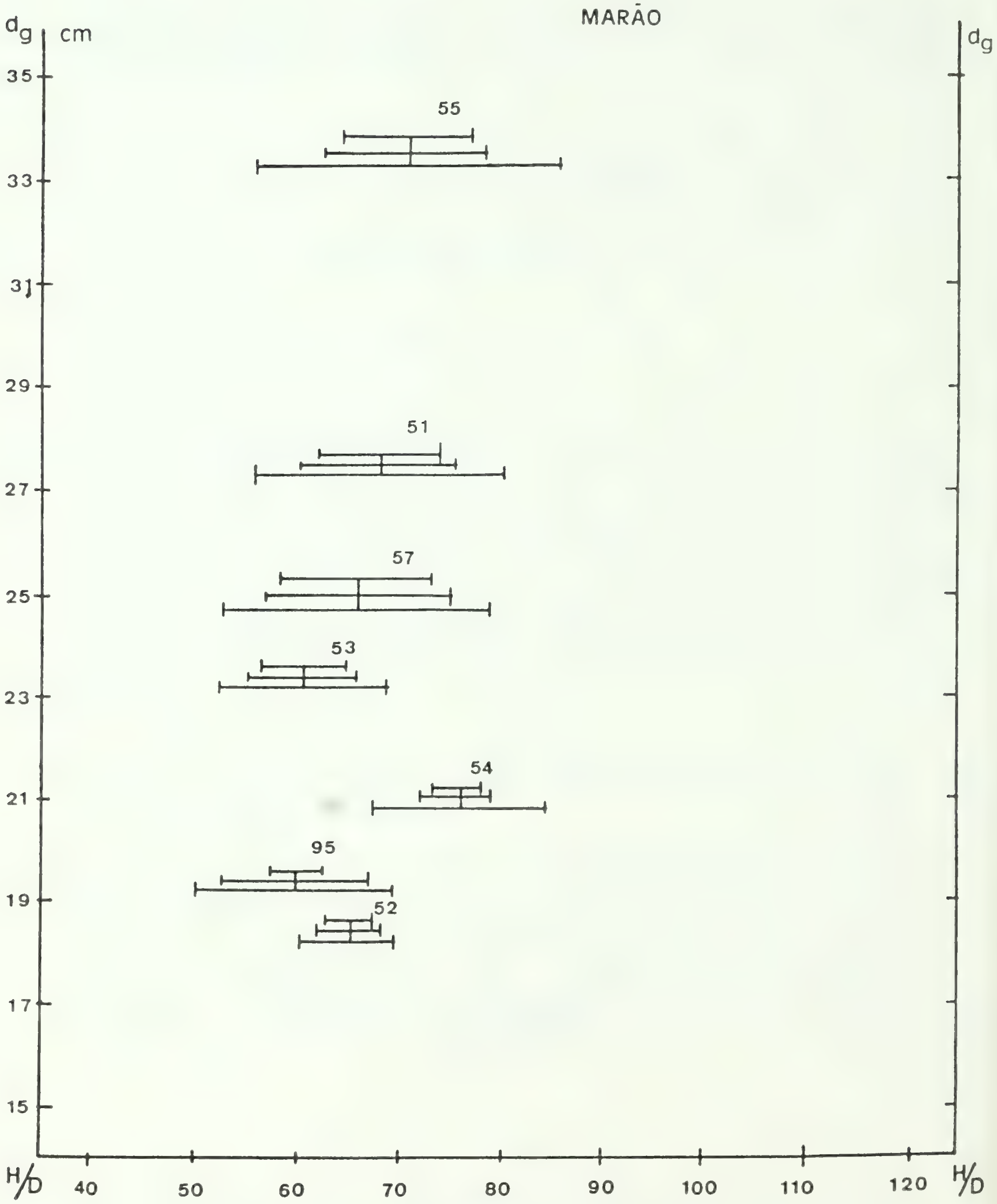
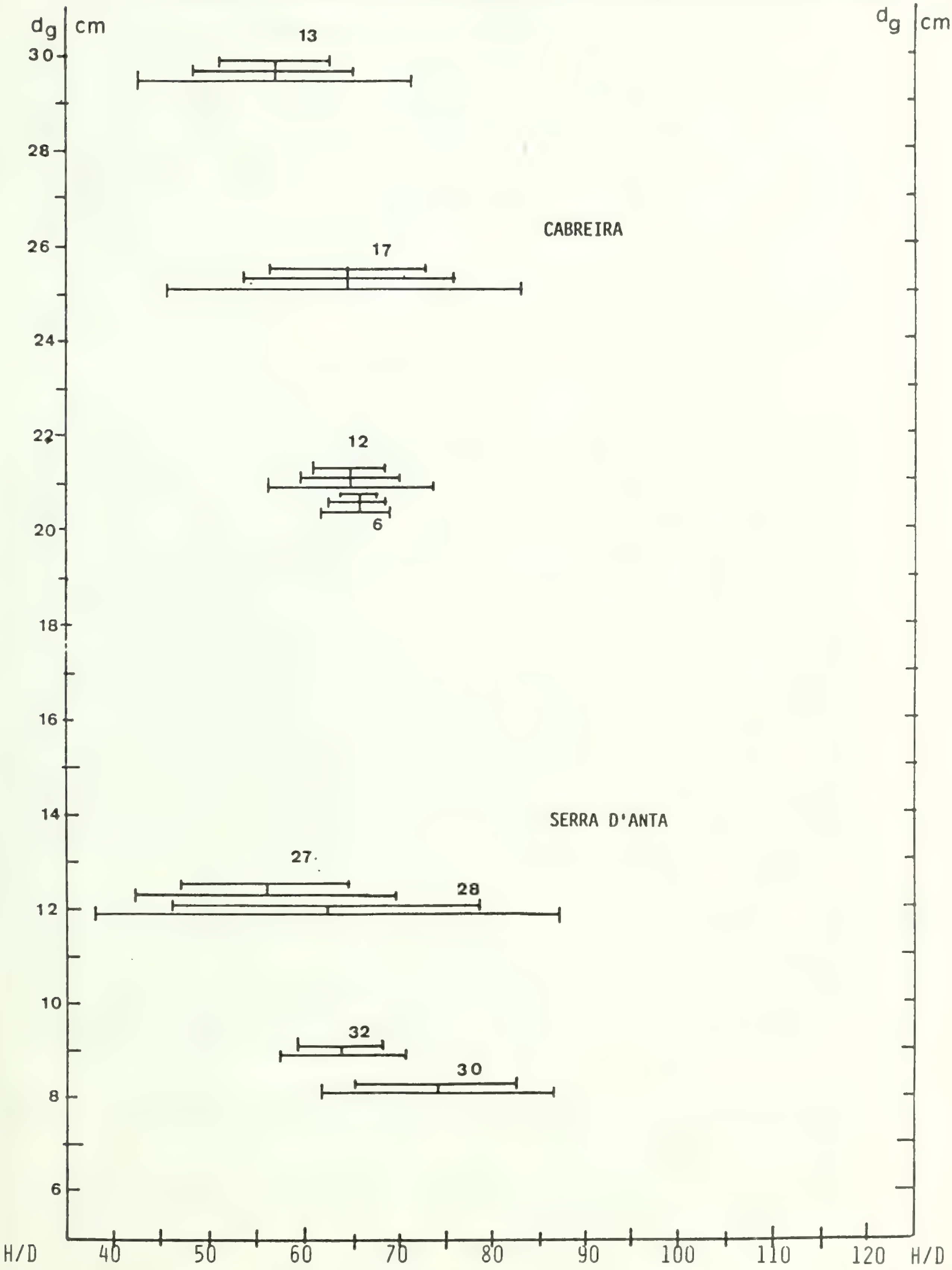


Fig.6: The mean H/D ratio (dominant trees) in growth series "Cabreira" and "Serra D'Anta" for the three significance levels. Plots 32 and 30 only 90% e 95%.



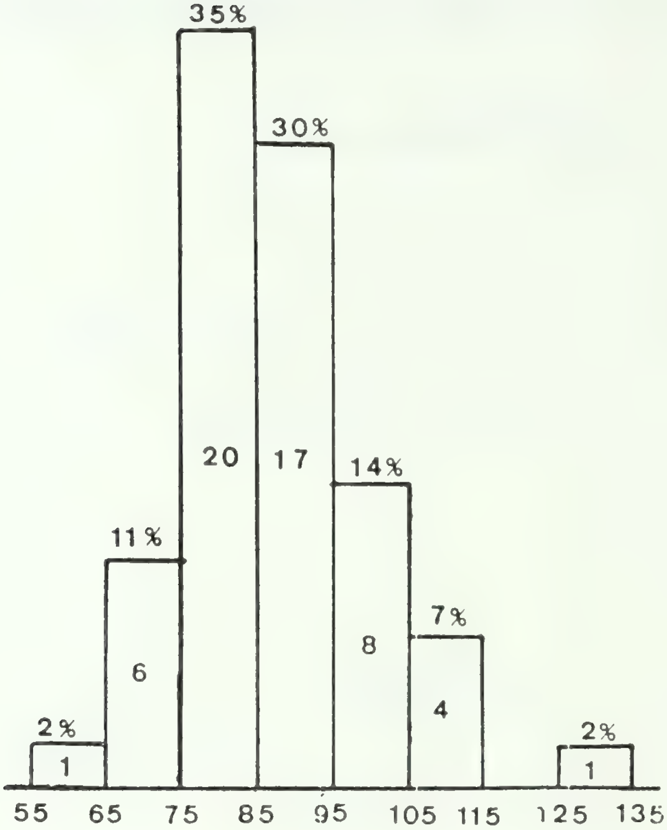


Figure 7. The h*/d* ratio (dominated trees) in the 57 inventory plots.

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DTREES - AN AUTOMATED STAND PRESCRIPTION WRITER AND HARVEST SIMULATOR[1]

Matthew Pelkki and Dietmar Rose[2]

Abstract. DTREES is a menu driven shell program that links four quantitative forest planning components in a fully automated software package. It uses a silvicultural expert system (Brand 1981a) to make harvest prescriptions. It uses the GROW subroutine (Brand 1981b) from the STEMS growth model (Belcher, et al. 1982) to project tree lists and a regeneration model (Ek and Brodie 1975) to regenerate stands after final harvest. Through a user controlled process, the system produces a list of alternative prescriptions for each stand over the entire planning horizon. This list of feasible stand prescriptions is then fed into the fourth component, a harvest scheduling algorithm called DUALPLAN.

INTRODUCTION

Forest planning, due to long planning horizons and the associated uncertainty, has been recognized as a complex and difficult undertaking. To assist in forest planning, quantitative tools have been developed for various aspects of the planning process, i.e., forest inventory and growth, silvicultural expert systems, stand-level investment analysis, spatial analysis, harvest scheduling and geographic information systems (GIS). However, few of these models have been linked and been fully integrated. Integrated Timber Management Scheduling System (ITMSS, Pelkki et al. 1987), being developed at the College of Forestry, University of Minnesota, allows user interaction and intervention in the planning process while automating the linkages between the various components. The key concept of this system are the automated linkages between each module, yet the user can enter into the process at any point and alter the inputs or intermediate outputs of the process. Thus, the system takes advantage of human decision-making abilities, while utilizing the computer to handle the huge data processing load that is required to analyze the various alternatives.

DESCRIPTION OF THE INTEGRATED PLANNING SYSTEM

Figure 1 depicts the major modules of the ITMSS. ITMSS is designed to automate the planning process while providing for user interaction and control at each stage of the planning process. Each ITMSS component is capable of functioning as a stand-alone system. The goal of ITMSS is to produce an operational timber-harvest schedule that meets with

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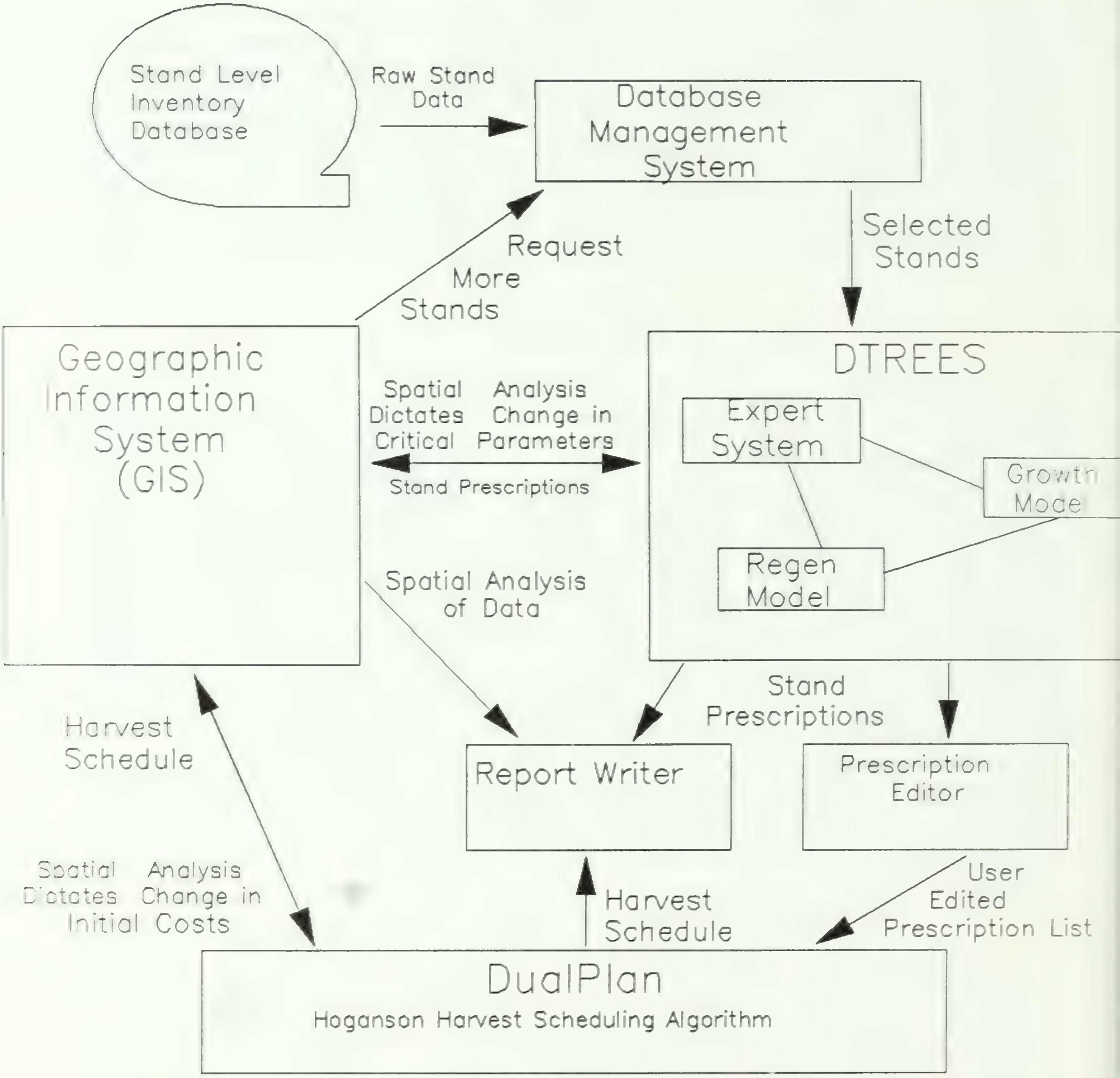
Stand Level Inventory Database
Raw Stand Data
Database Management System
Selected Stands
Request More Stands
Geographic Information System (GIS)
DTREES
Spatial Dictates Critical
Analysis Change in Parameters
Stand Prescriptions
Expert System
Growth Mode
Regen Model
Spatial Analysis of Data
Stand Prescriptions
Harvest Schedule
Report Writer
Prescription Editor
Spatial Dictates Initial Costs
Analysis Change in
Harvest Schedule
User Edited Prescription List
DualPlan
Hoganson Harvest Scheduling Algorithm

Figure 1. Integrated Timber Management Scheduling System (ITMSS)

forest-wide objectives and constraints without losing stand-level detail though data aggregation. ITMSS is designed to model the actual planning process as closely as possible. Currently, the DTREES prescription writer and the DUALPLAN scheduling algorithm are being developed and tested. The other components of the system are still in the preliminary phase of design and analysis.

DTREES is one component of that system. The DBMS component is used to select, from the stand-level inventory data base, the stands for which a timber harvest schedule is to be developed. Typically this is a large planning unit, composed of several thousand operational forest stands. From this list of stands, the DTREES system produces several sequences of management alternatives for each stand. These alternatives can then be edited or reviewed through the Report Writer/Prescription Editor modules. These modules provide management summary reports and provide an automated format for editing prescriptions. The prescription list then becomes the input for DUALPLAN, which selects an optimal prescription for each stand based on overall forest objectives and constraints. DUALPLAN is a microcomputer based application of the Hoganson harvest scheduling algorithm (Hoganson and Rose 1984). Because stand identity is maintained throughout the planning process, a GIS can be used for spatial analysis at any step of the process.

The primary goal of DTREES is to provide reasonable alternative harvest schedules and volume estimates for each stand. These prescription alternatives are silviculturally sound and are based on established biological guidelines. Ease and clarity of use was the second compelling objective. First, the area for which a plan is to be formulated is selected. Once the stand-level inventory for the area is obtained, the next step is to develop a set of technically feasible management alternatives for each stand. These alternatives may then be evaluated against financial, wildlife, recreation, and conservation objectives for the forest. Modifications can be made at this point in the criteria used to develop these plans, and new alternatives can then be developed. This iterative procedure may continue until all concerns are satisfied and alternatives do not seriously violate the objectives set for the forest. At this point, an optimization model may be used to choose between the stand alternatives, based on some objective function or criteria. The resulting "optimal harvest plan" can then go through another iterative process, with adjustments being made in the constraints and/or prescriptions.

DTREES: A Stand-level PRESCRIPTION WRITER

Decision TREE System (DTREES) functions as the "front-end" to a harvest scheduling algorithm. It provides a list of alternative management sequences for each forest stand by simulating management activities and responses. Included in DTREES system objectives are (1) use of a tree based growth projection system, (2) a modular systems design, (3) an understandable and user accessible silvicultural decision system, (4) avoidance of stand aggregation, and (5) a flexible inventory data interface which will accept current stand-level data bases.

DTREES provides a complete history of management actions, harvest and residual volumes for each "what if" alternative. It accomplishes this by integrating a silvicultural decision system, a growth simulator, and regeneration routines. For each stand-alternative a decision system evaluates current conditions and makes two harvest prescriptions, which are then simulated by removal of trees from an abbreviated tree list. Residual trees for each alternative are projected to the next planning period; any stand-alternative that undergoes final harvest is regenerated and a new stand tree list is generated. For the each planning period this sequence is repeated until the planning horizon is reached. Thus, over the planning horizon, a list of alternative management sequences and all pertinent data is derived.

DTREES is a menu driven stand-level prescription writer. Silvicultural decision trees (Brand 1981a) are at the heart of DTREES. The decision trees are derived from various silvicultural handbooks for Lake States cover types. These decision trees are used in such a manner that a variety of feasible prescriptions are obtained for a stand at each point in the planning horizon. The stands are modeled through time using the GROW subroutine (Brand 1981b) from the STEMS growth simulator (Belcher, et al. 1982). Coefficient data sets are available for the Northeast and Southeast regions of the United States, and as upgrades and improvements on GROW are made, the modular approach will make the transition to the latest model quite simple.

The third model type, integrated into DTREES, is the regeneration model. The extreme difficulty in modeling this period in a stand's history is reflected in the fact that tree level regeneration models are few in number for a few cover types in the Lake States, and non-existent for most. Aspen and red pine regeneration models are currently available (Ek and Brodie 1974; Belli 1986).

These tree models, through a user controlled interface, project a series of alternative management prescriptions through the planning horizon, and provide complete harvest and residual stand data for each alternative at each point in time. This data can then be fed into the GIS for spatial analysis and review, or be reviewed with the Report Writer, or fed into the DUALPLAN, the harvest scheduling algorithm.

DTREES assumes no predefined management sequences. Rather, it employs the decision-tree system by Brand (1981a) to evaluate all alternatives for a stand at every point in the planning horizon. The number of harvest actions are increased in number, and the intensity of intermediate thinning activities is infinite. Because the stand data is associated with a tree list, the growth response should be well modelled and the level of silvicultural detail be increased. DTREES takes advantage of the fact that no data aggregation is required, and processes each stand individually, projecting each stand's response to a harvest activity as it occurs. Because the data is not aggregated, several problems are alleviated. There is no need to spend time formulating timber class aggregates. The absence of aggregates means that the problem structure in the model mirrors the real world problem. Since restructuring timber aggregates is not needed, the altering of alternative prescriptions for a particular stand or cover type is accomplished relatively easily. Also, planners need not worry about the possibility of aggregating across some important timber class or spatial identities.

DTREES offers two methods with which users can alter prescriptions for stands. One method is through the DTREES expert system itself. By changing the critical parameters by which silvicultural decisions are produced, the prescriptions will be altered when re-run through DTREES. Another, faster method will be through the ITMSS Prescription Editor/Report Generator. This system will allow the user to eliminate prescriptions that are evaluated as unsuitable, and also allow the user to generate their own prescriptions for a stand directly. Currently, the Prescription Editor/Report Writer is still in the design phase. However, because of the automated nature of DTREES, the amount of man-hours required to alter a prescription matrix is minimal.

DUALPLAN: THE HOGANSON HARVEST SCHEDULING MODEL

Due to the size and complexity of strategic planning, stand aggregation has been used to reduce the problem size to a level which an optimization algorithm such as FORPLAN (Johnson, Jones, and Kent 1980) could handle. The results of an aggregated planning approach was a strategic plan which was not linked to an on the ground, operational plan.

Data aggregation is certainly one of the most pressing problems facing LP based forest planning models. The Hoganson timber scheduling algorithm solves the problem of data aggregation and drastically reduces computational time. Problems which would take years of computation time with Timber RAM or FORPLAN are reduced to less than a few minutes with the Hoganson algorithm (Hoganson and Rose 1984).

DUALPLAN is the microcomputer version of the Hoganson timber harvesting algorithm. The Hoganson algorithm, through problem decomposition, is able to optimize on an operational level without aggregating the input data set. Thus the strategic and operational plans are linked while an optimal harvest schedule is obtained. This algorithm allows for the decomposition of the dual of a Model I linear programming (LP) problem (Johnson and Scheurman 1977) into stand related sub-problems. These sub-problems are then solved independently, but based on an estimate of the marginal cost of producing various products. It is the relationship of these overall costs with each sub-problem that allows for the forest level optimization of the problem. The solution generated is then compared with the one desired by the linear programming primal. If the solution is not within a specified tolerance level, the marginal costs estimates are reevaluated and the problem is resolved. Although the primal LP is based on the minimization of costs, a simple module could be developed to transform this solution into one that shows the net present value.

Once a solution is reached, the model parameters, such as demand and price levels, could be reset, or data edited manually, and then the model rerun. This ability to resolve the model under different constraints tests the sensitivity of the solution to various demand and price scenarios. It can be used to develop an understanding of how changes in the present harvesting strategy will affect the forest in the future. Because no one would actually implement the one solution over a long planning horizon, this ability to see what alternatives are made available, or else eliminated in the future gives the planner much more of an insight into the implications of present decisions.

Another advantage of DUALPLAN is that stands are entered into the model as individual planning units, not as a portion of aggregates of various site and age classes. This level of detail produces a solution that is not only a strategic plan, but could also be used directly as the operational plan. It could also be used as an interface with a geographic information system, for a visual interpretation of the results of different solution.

REPORT WRITER AND PRESCRIPTION EDITOR

The model as it presently exists is just a portion of the planned model (Figure 1). One additional component of the system will be a data-base report writer and prescription editor. The prescription editor can be used to manually edit, delete or add stand prescriptions for any and all stands. This component allows the user to easily adjust, eliminate or add prescriptions as necessary, without re-entering DTREES. The report writer will take input from either DTREES or DUALPLAN (and from the GIS in the future) and convert the large data files into management reports. Because both DTREES and DUALPLAN are stand-level modeling programs, they produce large amounts of data for a planning area. The data files produced contain management information, but it is contained in a far larger set of data. The report writer summarizes the stand-level data and will produce a variety of reports of both the exception and summary types. Thus, the user will not have to manually interpret a large, often obtuse data file. Rather, after running DTREES and/or DUALPLAN, the user can summarize the output in standardized reports, and also see if there is anything unusual in the prescriptions or harvest schedule.

The type of GIS that would be most applicable to this planning system would be a polygon-based system. Due to the type of information stored for each stand, trying to store all of this in the layers of a raster system would not be efficient nor overly practical. Because a polygon system would work with the same units that the models work with, i.e., individual stands, it is the most suitable for this type of analysis. The GIS could be used to view initial stand characteristics, summarize information from DTREES and also summarize information from DUALPLAN. With this graphical analysis, the ability to find problems, such as contiguous stands with conflicting prescriptions, is improved.

SUMMARY

The DTREES component of ITMSS models stand-level forest planning as closely as possible. DTREES and DUALPLAN can perform region-wide analysis while still maintaining stand-level detail, thus obtaining an operational forest plan that is optimized on a regional basis. The advantages of a modular, menu-driven application system will allow the user more interaction and intervention capabilities within the planning process while taking advantage of the data processing speed of the computer. Inputs and outputs are designed to keep the planning process transparent to the user and to emphasize the extraction of useful information at each stage of the iterative planning process.

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ADAPTING FORMAN FOR TIMBER SUPPLY ANALYSIS IN MAINE

Robert S. Seymour and Ronald C. Lemin, Jr.[1]

ABSTRACT: FORMAN -- an age-class based forest development and management simulation model developed by the New Brunswick Dept. of Natural Resources -- was modified for forecasting future inventories and structures of Maine's timber resources. Data from the 1980 USDA Forest Service inventory of Maine (over 2100 plots) were used to stratify area by forest type, development class, and site productivity, and to formulate empirical yield curves. Procedures for aging and simulating development of multi-storied stands -- a problem which has limited application of age-based projection models in the Northeast-- are described.

INTRODUCTION

During the past decade, methodology used for large-scale timber supply analysis in the United States has evolved significantly (Haynes 1987), as TRAS (Larson and Goforth 1974), the stand-table projection model used in previous national assessments, has been largely replaced by TRIM (Tedder et al. 1987), an age-class, area-based model. For a variety of reasons, this conversion has not occurred in the Northeast. The great diversity in species and structure of Northeastern forests makes the conversion to an age-based model more difficult than in other regions where more classically even-aged coniferous stands dominate. Yet, many feel such a conversion is essential to accurately model development of the region's commercially important forests, which commonly exhibit even-aged, or two-aged stand structures (Seymour et al. 1986; Seymour 1986).

In the spruce-fir region of Maine and eastern Canada, a widespread outbreak of the spruce budworm (Choristoneura fumiferana) and concern over future wood supplies have recently stimulated development of age-based models (Seymour 1985). In Maine and New Brunswick, efforts have converged on adapting a single model developed in New Brunswick, now known as FORMAN (for FORest MANagement model), for a variety of timber-supply modeling uses, ranging from harvest scheduling on small properties to strategic analyses for an entire Province (e.g.: Erdle and Wang 1986). In this paper, we describe modifications made in the process of conducting an extensive analysis of Maine's timber supplies, commissioned by the Maine Department of Conservation's Forests for the Future program. While we have extensively modified the model's input and output options, the essential structure designed by New Brunswick analysts remains intact. Procedures may be applicable to adapting TRIM

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or other age-based models to model mixed-species forests in other regions.

MODEL DESCRIPTION

Alig et al. (1984) distinguished four components of timber supply analysis: land allocation, inventory projection, harvest flows, and timber investments. FORMAN's main focus is projecting inventories; harvest strategies and silvicultural investments are also modelled, but the scenarios are specified entirely by the user. There is no explicit provision for changing forest area.

To use FORMAN, one must derive the forest age structure and formulate a corresponding set of yield curves. The basic simulation unit is a **forest class**. If a small forest were simulated, a forest class could be a stand; on a large-scale, statewide analysis, a class is an aggregation of areas with a similar species composition, site, and stage of development. Identity of classes is maintained throughout the simulation. They can follow different yield curves after harvest and regeneration, and can also change curves during development to simulate thinning of established stands.

FOREST STRUCTURE

SITE PRODUCTIVITY CLASSES

There is no generally accepted method for classifying site quality in Maine. The USDA Forest Service used a site-index procedure (Scott and Voorhis 1986), which is often unreliable due to a lack of suitable free-growing trees. We elected to develop a simple soil-based system, using data obtained in the 1980 survey of Maine (Powell and Dickson 1984). Based primarily on drainage and rooting depth, and secondarily on texture of the B horizon and thickness of the organic pad, sites were classified into "poor", "fair", or "good" categories, assumed to correspond with the 20-50, 51-85, or 86+ cubic ft/acre/year classes used by the Forest Service.

DERIVED AGE-CLASS DISTRIBUTION

Perhaps the most difficult aspect of applying age-based models in the Northeast is determining the age structures of the various forest strata from conventional inventory data. The USDA Forest Service attempts to age every plot, but typically over half of the plots are classed simply as "uneven-aged", with no further description. Although these stands exhibit a highly stratified or irregular height structure, detailed studies (e.g: Oliver 1978; Marquis 1982; Kelty 1986) usually reveal that they contain either one or two age classes that can be traced to a single regenerating disturbance (Oliver 1981).

To overcome this aging problem, we derived an "effective age" structure using the canopy height and soil productivity class. Given the plot height, the site index curves formulated by Scott and Voorhis (1986) were solved "backwards" for age at both the upper and lower bound of the productivity class (derived from the soil properties). The midpoint of these two ages was then assigned as the "derived age class" for that plot (Fig. 1). For species that typically reproduce as advanced regeneration, this derived age was further reduced by subtracting the age at a height = 1 ft (the estimated height of seedlings when released from overstory competition).

Results were found to conflict with earlier work which had estimated the spruce-fir age structure from measurements of chronological age, coupled with records of harvesting and natural disturbance. For example, the derived age structures for the good and average site classes in the spruce-fir type show a large area in the 40-year class, and relatively little in 1-10 year-old stands. This is not consistent with the known history of disturbance in the spruce-fir type (Seymour 1985), which was characterized by extensive cutting and budworm mortality between 1870 and 1920, followed by several decades where little regeneration cutting was done, then by increased harvest and budworm activity beginning ca. 1970.

We offer two possible reasons why the height structure does not correspond with the suspected harvest and natural disturbance history. First, past work may have underestimated the importance of agricultural land abandonment, which created millions of acres of new forests in Maine since 1900. It is quite plausible that several hundred thousand acres reverted during the 1930's and 1940's that has since developed into spruce-fir or tolerant hardwood stands. This rationale is consistent with the preponderance of this age class on good sites, where agriculture would have been concentrated. Another plausible hypothesis is that much past harvesting activity has not, until recently, led to the development of classical even-aged stands which follow a free-growing height-development pattern for their entire lives. Maine's important timber types are dominated by shade-tolerant species such as red spruce (Picea rubens) and sugar maple (Acer saccharum) which can persist for decades as a slow-growing understory, respond abruptly to release, and continue development as a free-growing tree. As a result, stands now apparently in 30-50-year age classes may actually be 10-40 years older if they regenerated between 1900 and 1920 but were not released from overstory competition until 1930-50.

If this is true, one could argue that the derived age structure more accurately portrays the true stage in development, and thus is a better predictor of future yields, than the actual chronological age. In any case, past development is irrelevant; the main reason age is even needed is to link stand development to passage of time in the future. Since this derived age is also used as the independent variable in formulating yield curves, the crucial assumption is that dominant overstory trees will continue to grow as the height-development curve predicts for that soil-site class. If this does not hold, then the derived yield curves must be lagged accordingly, to "synchronize" height development and volume growth with passage of time.

The derived spruce-fir age structures are quite different among the three site classes (Fig. 2), a pattern also evident in other types. The

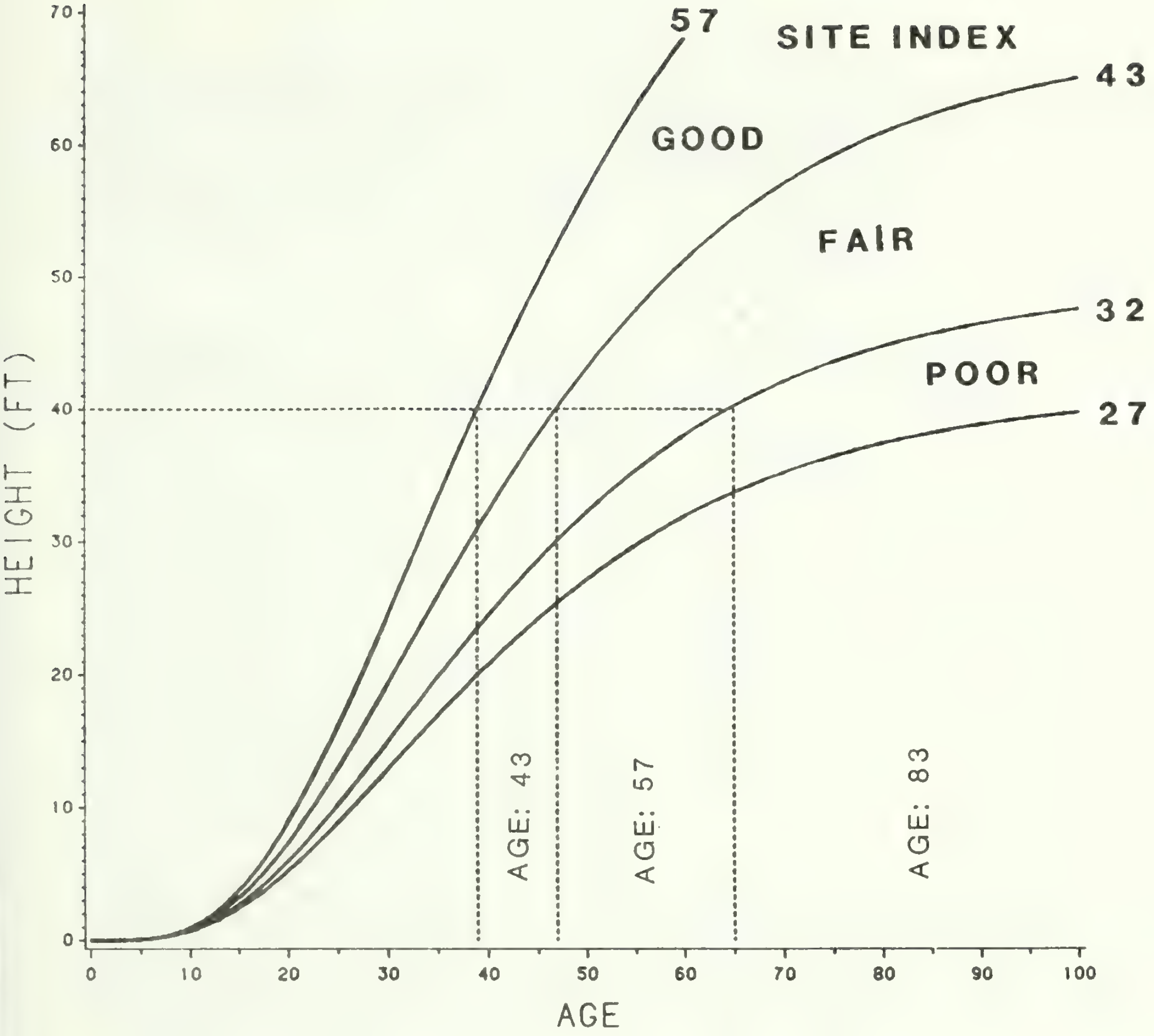

Figure 1. Example showing derived age for a spruce-fir plot with canopy height = 40 ft.

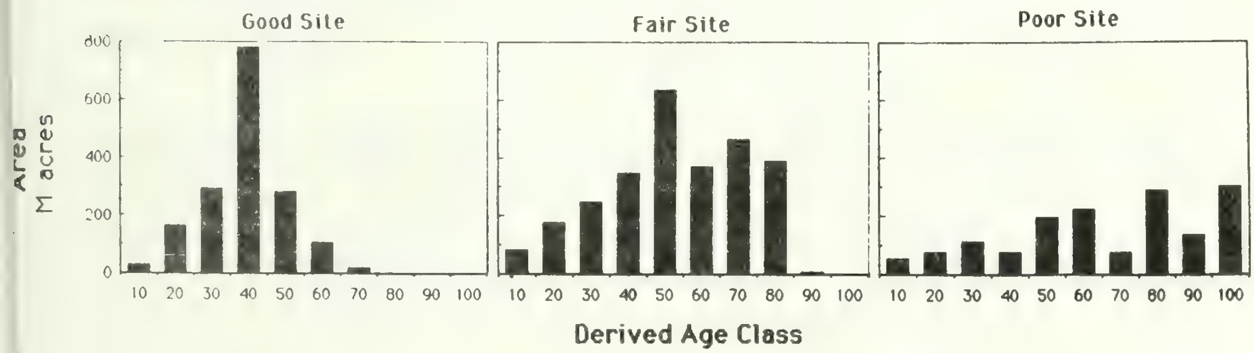

Figure 2. Comparison in derived age structures among site classes, spruce-fir type.

observed distributions follow a long-suspected but poorly documented phenomenon: if stands are harvested when they reach a certain volume, old stands rarely develop on good sites, but tend to dominate poor sites where the threshold volume takes longer to accumulate (Monsereud 1984). In this situation, averaging age structures across all site classes would tend to underpredict future growth, because site quality of the highly productive middle-age classes is underestimated.

Subdivision of Irregular-height Plots. Many plots show substantial variation in height among the 5 points in the Forest Service's cluster plot design, suggesting a two-aged stand structure. Using a canopy height of 25 ft as the boundary between "old" and "young" age classes, all 2110 plots were subdivided into the 6 possible classes on the basis of the heights of the individual points. Plots with 4/5 or 5/5 of the points in either young or old were assigned entirely to the dominant age stratum, on the grounds that only 20% of a given stand should not considered a separate age class; 87% percent of the plots fell into this "even-aged" category. Plots with a 3/2 or 2/3 split were subdivided into separate age classes based on the average heights of each component. USFS area-expansion factors were apportioned 3:2 or 2:3 to assign acreage to the subdivisions. In effect, this takes "real" acres and creates two artificial classes for simulation purposes.

FOREST TYPES

In addition to its age and productivity, FORMAN allows each forest class to be assigned to one of 12 "management units". These are primarily intended to represent geographic subdivisions of the forest which have unique harvest schedules, such as a district within the operating region of a large company, or a ranger district on a National Forest. For the analysis of Maine, we used management units to represent the eight major forest types in the State: spruce-fir, tolerant hardwood, white pine, intolerant hardwood, hemlock, swamp conifers, oak, and old-field hardwood. Since FORMAN can accept up to 12 such units, four units are available to model other forest strata which may warrant separate harvest schedules. For example, we used this feature to separate out zoned deer wintering areas where harvesting is constrained.

YIELD CURVE FORMULATION

Analysts have three options for incorporating forest growth into timber supply models: adapting published normal or managed-stand yield tables; fitting empirical yield curves to same data used to derive forest structure; or generating yield tables from an appropriate stand-level model. We combined the first two approaches: empirical curves were used to predict yields of the present unmanaged forest, whereas published curves were used for managed stands.

Empirical yield curves have several weaknesses. It is difficult to determine the harvest history of a plot and to decide whether such plots should be included in the curve-fitting process. Also, empirical trends reflect only the average volumes of stands which survive to that age. With preferential harvesting of high-volume stands, the surviving stands represent an increasingly poorer component of the original population of that age class. As a result, true net growth from one age class to the next can be consistently underestimated, especially if site classes are not used. Despite these drawbacks, empirical curves do represent average conditions quite well, especially in large-scale models where thousands of stands must be aggregated into a single forest class.

To accurately model the timber markets in Maine, we formulated yield curves for seven species groups: spruce-fir; white pine; northern hardwoods; aspen-paper birch; hemlock and other softwoods; oak and ash; and northern white cedar. Yield curves are needed for each site x type group where the species is present; in theory, this would require a maximum of 8 types x 3 site classes x 7 species = 168 curve sets. We combined site classes in all but the spruce-fir and tolerant hardwood types, reducing the number of sets to 84.

Because each species is typically marketed for a variety of products, yield curves must not only predict total yields but also product breakdowns. We developed curves in terms of three units: total net merchantable volume; net cubic volume of the sawtimber portion, expressed as a percentage of the total volume; and net weight of the unmerchantable parts of the stem and undersize trees. Using the 1980 Forest Service data for Maine, volumes/weights were summarized by species groups and 10-year age classes for each of the 12 site x type classes. Statistical fitting procedures were not used. FORMAN specifies yield curves by a series of vertices (volume/age or weight/age pairs). In most cases, we simply used the mean volumes by age class as the vertices, using subjective smoothing where necessary to avoid illogical trends resulting from small sample sizes.

Managed Stand Yields. Intensive even-aged management techniques common in other coniferous forest regions have only recently been applied in Maine. Consequently, little long-term response data are available. We used managed stand yield tables derived by Bailey and McNally in Nova Scotia, which have been formulated with a simple calculation model that generates cubic volume yields for any site index, planting/spacing density, and stocking level.

MODEL CALIBRATION

After curve sets are formulated and the effective age structure derived, the initial forest structure must be calibrated so that the stocking levels in the model forest agree with actual forest totals. This process is facilitated by a vertical scaling factor for each yield curve, which can be varied until nearly perfect agreement is achieved.

Once the initial forest is calibrated, the model should then be tested to determine if it faithfully reproduces historical development. In our case, we began simulations in 1980, ran for 5 years, and compared results with an interim, mid-cycle remeasurement of the spruce-fir resource carried out in 1985. This presented a difficult problem, since the 1980-85 period experienced abnormally high tree mortality caused by the spruce budworm. Unlike the Green Woods model (Seymour et al. 1985), FORMAN's empirical yield curve design does not explicitly predict catastrophic loss. We simply increased the 1980-85 harvest to 315% of the actual level, which gave close agreement with the actual 1985 inventory.

MANAGEMENT STRATEGIES

One strength of FORMAN is its ability to represent a diverse array of "real-world" timber management strategies. No harvest optimization is attempted; one simply begins with a desired wood flow, and modifies the harvest and management until a satisfactory outcome is obtained. Harvest volumes are specified by 5-year periods, and can be apportioned among various forest types. Flexible harvest rules allow forest classes to be queued according to: total, sawtimber, or biomass per acre; to presalvage mortality of declining stands; or to minimize cost. Planting and thinning can also be varied by five-year periods, and prioritized among forest classes, for example to simulate planting of only good quality sites.

CONCLUSIONS

We believe FORMAN offers great promise for timber supply analysis at several levels, ranging from regional projections done by the USDA Forest Service, to timber supply analyses for both large and small public and private forests. Our revised version, known as "FORMAINE", is programmed in Fortran 77 and runs quickly on an IBM-compatible PC. It handles up to 800 forest classes and 200 yield curves, and thus can readily deal with any real-world problem. Although not technically sophisticated, it allows any user with a general knowledge of timber management principles to carry out simulations rapidly and tractably. This is arguably a better approach than using complex, "black box" models where the approach is to derive "the answer" in one very detailed run.

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MULTIPLE USE FOREST MODELLING IN AUSTRALIA

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ABSTRACT. A multiple use forest model has been developed for a native eucalypt forest in Australia as part of a student exercise. It has recently been adapted to run under FORPLAN. A full-scale application of an advanced planning process incorporating the use of a modified FORPLAN has begun in a forest region in Victoria.

Australian forest services and industry have been using largescale and longterm computerized planning models since the late 1960's. Although some of the earlier models were simulators (e.g., Gibson et al, 1969), most of them were linear programming models of the Model I type, which often incorporated stand growth simulators in the matrix generators (e.g., Dargavel, 1978). Undoubtably this approach was strongly influenced by a visit to Australia in 1969 by the late Jerry Clutter.

These have been almost exclusively timber harvest scheduling models and have been most successfully applied to pine plantation systems. Unfortunately most of these efforts were shelved as the enthusiastic developers moved on to new positions and only a few models, in much modified form, are still being used. Currently there is a new wave of development, with much more of the utilization system being incorporated into the models.

One of the earliest illustrations of the potential of linear programming in the Australian forestry literature was an application to an extensively-managed eucalypt forest in Victoria (Paine, 1966). However modelling of the

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extensive state-owned native eucalypt forests has been mostly confined to modelling the growth of evenaged regrowth stands (e.g., Weir, 1972). At least part of the reason for this is that in the 1970's the emphasis in Australian forestry changed in general from management of the native forests to the planting of extensive areas of exotic conifers. The fairly intensive management of the higher quality eucalypt forests as occurred in the 1950's and 60's was replaced by a caretaker role, as the aim of management altered to one of eking out the hardwood resource until the fast-growing pines captured the market. Coincidentally a strong conservation movement was able to have considerable areas of the remaining state-controlled old-growth forests converted to national parks in which harvesting is banned.

The often-bitter controversies which raged over these land-use changes resulted in a considerable increase in public awareness of the value of the eucalypt forests for supplying a variety of community needs. In the last decade there has been a significant change in public attitudes to the Australian "bush" --- in the middle-class suburbs in which most Australians live there has been a change from indifference to a romanticization of native flora and fauna, increasing concern for the protection of native forests from disease, fire and logging, and a reduction in concern for the preservation of often ailing timber industries and communities. Most of the highly productive forests are within a day's journey of the major population centres and, perhaps more importantly, are within hours of most of the coastal resorts to which Australians flock for vacations. They also often are the headwaters for these coastal towns' water supply. Increasing conflicts are thus inevitable.

The response of the forestry industry to these attitudinal changes has been to modify cultural practices to reduce detrimental environmental effects but at the same time to insist on the importance of utilization of the timber resource for preserving a viable rural community as well as for supplying a valuable raw material. In several states, "multiple use" has been implemented through a zoning approach by which non-wood benefits are given primacy in specified zones and timber production (with varying degrees of environmental safeguards) has priority in the remaining areas. One problem with this approach is that it is supply-driven: little account is taken of the *demand* for the various goods and services, and in particular regional variations in demands are not considered.

In two states (Western Australia and Victoria) the forestry agencies have recently been amalgamated with other land and resource agencies and the management of all public lands decentralized into regions. The state of Victoria (about the size of Minnesota) has been divided into 16 new regions which have considerable autonomy. The Department of Conservation, Forests and Lands (DCFL) has been subjected to a series of strategy- development efforts, commencing with an Inquiry into the Timber Industry conducted by Professor Ian Ferguson, who suggested inter alia that forest planning be conducted at the regional level with effective public participation. These recommendations were upheld by the Government's 1986 Timber Industry Strategy which confirmed that state forests should be managed for multiple uses, where all forest values and uses will be safeguarded. It further requires that long-term planning be carried out to ensure that forests continue to provide sustainable yields in perpetuity.

These requirements indicate a need for a degree of intensity of planning quite unlike that previously practiced. In other states the pressure to increase planning intensity has come from conservationists' ploys to place forests which are of concern to them on the Register of the National Estate or even to accord them World Heritage listing, both of which require Commonwealth Government intervention if conservation values are threatened. One such forest is the Coolangubra State Forest in southeastern New South Wales, administered by the NSW Forestry Commission.

THE COOLANGUBRA MODEL

Forestry students at the Australian National University (ANU) spend much of their final year on various aspects of forest planning. Coolangubra State Forest was chosen as an interesting application for a student planning project because it is (or was) being roaded and logged essentially for the first time, thus planning exercises could be of some interest other than purely academic (Turner, 1986). As well as supplying sawlogs to a local mill, it is part of the supply zone for a large woodchip industry exporting to Japan. It is also recognised as having unique qualities as arboreal mammal habitat, of such value that conservationists have forced a ban on logging until environmental impact reviews are satisfactorily completed. Conservationists are claiming that it should be designated as national park on the grounds that the forest is one of the last remaining untouched escarpment forests and has non-timber values that will be adversely affected by logging. Industry claims that the forest contains much of the remaining sawlog resource of the region and its removal from production could close mills in the area and that a ban on woodchipping could jeopardize that industry.

The students acted as the interdisciplinary planning team, and were assisted by a technical team of departmental staff. From their knowledge of the forest the students composed a list of issues, concerns and opportunities, and a list of quantitative decision criteria was developed. The technical team built a computerised map base of the 22 000 hectare forest to derive the size and location of homogeneous areas ('analysis areas'), and wrote a computer program to input the students' data to a standard LP computer program (FMPS).

THE GEOGRAPHIC DATABASE

A geographic database was developed by imposing a 200m square grid on maps of the forest and reading off information which was then computer encoded. Included were topographic maps to create an elevation layer which was then used to derive slope classes, a geology map and a "Stand Condition Class" map. These layers were entered into a database using TOMIS (Myers 1983) as the geographic information system (GIS). TOMIS was used to model new layers derived from these and other sources. The finally selected layers were: Stream Corridors, Road Corridors, Arborial Habitat, Erosion Potential, Timber Growth Potential, and Stand Condition Class.

In all, 124 analysis areas were recognized, after those of less than 40 ha were collapsed into the most similar analysis areas.

PRESCRIPTIONS

Four basic silvicultural prescriptions (one clearcut and three selection) were considered. Time of initial entry ranged over the full planning period of 50 years (5 periods of one decade).

Under the clearcut regime, 90% of the standing volume was to be removed. A pulpwood thinning of the second-growth stand was assumed, with age at thinning depending on the growth potential class.

Three selection regimes were considered: a heavy selection regime (75% of volume removed in first cut), a single tree selection regime (50% removed) and a group selection regime (also 50% removed but somewhat longer cutting cycle lengths). In all cases the second entry time depended on the growth potential class.

ECONOMIC DATA

Costs for annual maintenance, and for marketing for the various treatment types, and the revenues (in the form of stumpage values) for sawlog and pulpwood were gathered from the Forestry Commission. The value of recreation was determined from the few available consumer surplus studies conducted in Australia, and water was priced at the approximate marginal cost to the consumer in the area, reduced by reticulation and storage costs.

YIELD DATA

Yield models were developed for timber (sawlogs and pulpwood), water quantity, sediment production, wildlife value and recreation visitor days. In all cases actual values were dependent on prescriptions, time since operations and analysis area characteristics.

Timber volumes were estimated by stand condition classes from data supplied by the Forestry Commission. Net growth of old growth stands was assumed to be zero and growth of second growth was estimated by extrapolation from yield models developed for similar species in Victoria.

Water yields were modelled after trends found for experimental watersheds in Victoria adjusted for very obvious differences in vegetation, soils and climate. Sediment yields were similar extrapolations from Western Australia data.

Wildlife values were derived by using estimated number of arboreal mammals as a proxy. The basis of estimates was an experimentally logged and monitored area on the western edge of the forest. Recreation potential was estimated as total visitor days, using foresters' estimated of past use as the starting point and assuming a compounding increasing trend, dependent again on prescriptions and analysis areas.

RESULTS

Each student group formulated a management alternative in the form of desirable target values to be achieved by decades over a 50 year planning horizon, in sawlogs, pulpwood, water yield, sediment yield, recreation potential, wildlife quality and financial budget. These values were set as constraints and the LP run under an objective function of maximising the total present net worth of the forest. Student groups were thus able to compare their strategy against others.

The model has been developed by two successive student classes. There are major deficiencies in the basic data and yield models but the relationships are reasonable enough to provide useful results for the student planning exercise. However the latter required that areas of the forest be zoned according to a "preferred management priority" procedure and this was not possible with our simplistic matrix generator. Thus the results did not accurately reflect the student groups' preferred strategies.

FORPLAN IMPLEMENTATION

Rather than revise the matrix generator it was decided to acquire a copy of FORPLAN Version 2 which does accommodate the zoning approach. In January 1987 a copy of Release 12 of FORPLAN Version 2 was received from the USDA Forest Service at Fort Collins (B. Kent, pers. comm.). This was implemented on the ANU's Univac 1108 and the Coolangubra model was successfully run on it shortly before the Univac was decommissioned in June. FORPLAN has now been adapted to run on the University's VAX 8700 using MINOS (Murtagh and Saunders, 1983) as the linear programming package. This will be used with this year's students.

THE OTWAYS FOREST MANAGEMENT PLANNING PROJECT

Despite the difficulties encountered in the Coolangubra exercises, the concept of using a model to evaluate multiple use management options in a eucalypt forest was sufficiently demonstrated that the author and a close associate, Dr John Dargavel of the Centre for Resource and Environmental Studies (CRES) at the ANU, were encouraged to propose the approach to the Victorian DCFL. After considerable negotiation, a two and a half year cooperative project involving ANU and DCFL personnel is now underway to apply these advanced planning techniques to the Otway Region forests in southwestern Victoria and to develop the first regional forest plan, to be a prototype for all other regions.

A FORPLAN-type model for the region's 90 000 hectares of state forests is now being developed. The forests supply about 40 000m^3 of hardwoods (mainly *Eucalyptus* spp.) and 35 000m^3 of *Pinus radiata* sawlogs per year to nine sawmills directly employing about 500 persons (5% of the regional workforce). Up to 500 ha of native forest are logged annually mostly by clearcutting. Although pulpwood operations have been carried out in the recent past in conjunction with sawlogging, none are permitted at the moment even to remove the considerable quantities of residual wood. The timber industry has been guaranteed supply at about existing levels for the next 15 years. The Otways support diverse vegetation communities ranging from cool temperate rainforests (in which logging is banned) to woodlands with heath understorey. Rare and endangered flora and fauna occur in the forests and preservation of these is required. There are eight proclaimed domestic water supply catchments in the Otway Region and the Ranges supply water to about a quarter of a million people. The Region supports over 1.6 million visitors annually and the state forests are intermixed with 60 000 ha of parks and reserves.

At issue are whether logging is detrimental to landscape values, accelerates soil erosion and degrades water quality, whether alternative silvicultural practices would reduce these effects and still support regeneration, whether integrated pulpwood/sawlog operations would be socially and environmentally acceptable, whether tourism could pick up the employment slack if timber production were curtailed, etc. Opposition to logging is strong among some groups and damage to logging equipment is not unusual. The area is thus ripe for multiple use planning.

The Planning Team is about to embark on an initial round of public participation to further define the issues, concerns and opportunities, and this will be followed by the finalization of decision criteria and subsequent decisions on data needs. Meanwhile a comprehensive geographic data base is being developed using the Arc/Info GIS running on the DCFL's Prime computers. At this stage it is clear that the following layers will be digitized and included in the database and will form the basis for the definition of analysis areas:

Geology/ geomorphology; Topography and streams; Water catchment boundaries; Erosion hazard classes; Roads; Forest types; Stand classes (age/quality); Cultural boundaries; Management boundaries.

YIELD MODELS

Timber yields will be derived from several yield models currently used by the DCFL.

(a) STANDSIM, developed for evenaged stands of mountain ash (*Eucalyptus regnans*) by Opie (1972), is a distance-independent tree model which was used in the optimization package called MASH (Weir, 1972). MASH was constructed to help plan the utilization of extensive areas of mountain ash regrowth in central Victoria resulting from the disastrous 1939 fire.

(b) MESSIM was developed by B. A. Kilgour to model the lower quality unevenaged cutover messmate (*E. obliqua*) of southwestern Victoria. It is a distance-independent tree model which predicts dbhob increment as a function of dbhob, basal area density, site index, and past logging history.

(c) For its pine plantations the DCFL is constructing a sophisticated planning simulation system called FRIYR. This uses a stand model which will be used to supply input to the Otways model.

As yet no work has been done on yield models for other forest outputs --- the project team can call on a number of experts within DCFL and the ANU to assist.

PRESCRIPTIONS

The mountain ash forests are conventionally harvested by clearcutting followed by a hot fire to remove as much as possible of the post-logging debris, and then hand or aerial sowing if necessary. It is widely believed that this regime is essential for adequate re-establishment. Some alternative evenaged and \selection management regimes will be incorporated into the model even though the regeneration results may be uncertain.

Our intent is to incorporate socioeconomic variables directly into the optimization model, so that the effects on forest management of employment and industrial restructuring strategies can be directly evaluated.

DISCUSSION

There are very real difficulties in applying multiple use modelling to native forests in Australia. Some of these problems are similar to those found with their application to U.S. national forests (Johnson, 1987). However one not specifically identified by Johnson is the widespread scepticism that there is adequate data to support the intensity of modelling required for an optimization model. Evidence is lacking on the ability of sensitivity analysis to compensate for scanty data and coarse environmental-effects models. There are hard questions as to the cost-benefit relationships of this intensity of planning. There are doubts as to whether decision-makers will wish to or be able to fully comprehend the complexities of the modelling approach, let alone that the many critics of the multiple use approach will find it believable. There is thus understandable interest in alternative planning approaches of which the suitability analysis approach seems most popular. However these approaches generally deal only with the supply side of the resource and are therefore inadequate when multiproduct demands and efficiency goals are included in the system.

It is an unfortunate fact that the efficient management of a forest for a variety of often incompatible outputs and environmental constraints is not a simple matter and simplistic techniques will not do the job. In Victoria we hope to demonstrate that these advanced planning techniques do have value in analyzing and displaying the effects of management alternatives.

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OPTIMIZING SPECIES COMPOSITION IN MIXED, EVEN-AGED STANDS

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ABSTRACT. Volume yields and financial returns from Finnish even-aged spruce-birch stands were analyzed based on optimum thinning and rotation management regimes. The mixed stand with an optimal species composition was superior to both of the single species stands, considering volume as well as net revenue maximization. Methods to solve the associated optimization problem are discussed.

INTRODUCTION

Compared to single species stand optimization, additional questions in mixed species optimization in even-aged stands include the optimal species composition of the initial stand, the species mix during rotation and the final harvest age of each species. The economic analysis is similar to the single species case, only some additional state and control variables may be defined. The size of the optimization problem is increased by additional tree species and optimization methods suitable for single species analysis may become unavailable. This refers especially to dynamic programming which has so far been the most popular stand optimization technique.

Three different types of mixed species growth models may be distinguished based on the model form regarding variables describing competition for growing space: (1) competition is not species specific (Agestam 1985, Bullard et al. 1985), (2) competition is species specific (Wykoff et al. 1982), (3) competition is mixture specific (USDA Forest Service 1979, Mielikäinen 1980, 1985, Lynch & Moser 1986). The models of group (1) typically have one variable that represents the competition due to all other species in the stand, e.g. basal area sum of other species. In models of group (2) each species contributes differently to competition in the stand and the model contains e.g. separate basal area variables for each species with unequal coefficients. The models of group (3) apply only to predefined species combinations. They have the potential to describe accurately how tree species with individual ecological characteristics interact.

One of the most interesting questions regarding mixed stand management is the existence of the so called mixture effect which implies that a given number of trees grow faster when intermingled as a mixed stand than when growing as separate pure stands. The idea of the mixture effect is based on the assumption that two ecologically different species would utilize the growth potential of the site to larger extent than a single species. Models of group (3) should reveal the mixture effect if it exists. Models of groups (1) and (2) may show the mixture effect if it exists and the data set happens to consist of plots with species combinations where the mixture effect is present. These model groups may also fail to recognize existing mixture effects.

In the above the mixture effect was defined in biological terms. It means that at some point of time during the rotation the growth of a mixture exceeds the average of the growths of the pure species, weighted by species proportions. From a managerial point of view we may define a mixture effect when, say, the total growth during rotation or the discounted net revenues from the stand are greater for a mixed stand than for a pure stand. This may take place also when the tree species have differing growth rhythms although at no point of time the biologically defined mixture effect exists. In a two species case we would utilize the periods of fastest growth of both of the species by allocating growing space for them accordingly during the rotation.

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In this study the optimal species composition of a mixed stand of Norway spruce (*Picea Abies* Karsten) and silver birch (*Betula pendula* Ehrh.) is determined. Optimal thinnings and rotation are derived for maximum mean annual increment and soil expectation value. Two optimization methods (dynamic programming and direct search with the method of Hooke and Jeeves) are also compared.

STAND SIMULATOR

The whole-stand growth model for mixed stands of spruce and birch in Finland is adopted from Mielikäinen (1985). The models for predicting the volume growth percentage of the two species are based on stand age, total stand volume and birch percentage of volume. When transformed to functions of volume by tree species the models become

$$I_{vs} = 9.553\ T^{-.6477}\ V_s\ (V_s + V_b)^{-.5577} \tag{1}$$

$$I_{vb} = 4.844\ T^{-.9317}\ V_b^{.7646}\ (V_s + V_b)^{.0030} \tag{2}$$

where I_{vs} and I_{vb} are the volume increments of spruce and birch, respectively, during the following 5-year period (m^3/ha/yr), T is the breast height age of the stand, V_s is the volume of spruce (m^3/ha), and V_b is the volume of birch (m^3/ha). Some observations on the growth functions may be made. With increasing age, the growth of birch slows down more rapidly than that of spruce. Birch reduces the growth of spruce but birch growth is practically independent of spruce volume. This feature seems to result from the tendency of birch to overtop spruce in young stands.

Due to lack of more elaborate models some simplifying assumptions regarding stand development are made. Instead of a mortality model the following growth reduction procedure was constructed. Based on the data set for growth functions the maximum stand volume (V_{max}, m^3/ha) giving undisturbed growth was defined as

$$V_{max} = 235. + T \tag{3}$$

where T is stand age. When the predicted stand volume (V) exceeds V_{max} it is reduced by a factor x which was arbitrarily chosen to produce plausible growth reductions for overstocked stands:

$$x = 1. - 2.24 \left[\frac{V - V_{max}}{V_{max}}\right]^{1.5} \tag{4}$$

To follow the development of average tree size, the number of trees is taken as a state variable. It is not used in the growth function and, in the absence of more detailed information, it is assumed that the average tree sizes of both species are always equal.

Thinning type is assumed to be mechanical such that the number of trees removed in a thinning is proportional to the volume removed.

To divide harvest volume into product classes two types of equations are used. The proportion of nonmerchantable wood is obtained using equations in Valsta (1986). The percentages of sawlog volume are predicted as functions of stand age, based on Mielikäinen (1985). The rest of the volume harvested is pulpwood.

Sawlogs and pulpwood are priced individually and the following net stumpage prices (FIM/m^3) are used: 180 for spruce sawlogs, 100 for spruce pulpwood, 190 for birch sawlogs (used for veneer) and 80 for birch pulpwood. Along the lines of the price agreement between the Finnish forest industry and the farmer's association the stumpage prices are adjusted based on the average tree size and the volume per hectare harvested to reflect logging cost differences.

OPTIMIZATION METHODS

Three most applicable optimization methods for stand level analysis are, in my opinion, dynamic programming (DP), discrete-time optimal control (DTOC), and direct search (DS), e.g. the Hooke and Jeeves' method (Brodie & Haight 1985, Haight 1987, Roise 1986). The compatibility of these optimization methods with some model and solution characteristics may be summarized as follows:

	Compatilibility of optimization method		
	DP	DTOC	DS
Model characteristic			
not differentiable	yes	no	yes
many state variables	no	yes	yes
Solution characteristic			
global optimum found	yes	no	no
accurate optimum determined	no	yes/no	yes

It can be seen that none of the optimization methods fulfills all of the requirements stated above. It is a question of the art of optimization to judge which of the characteristics are decisive.

The results are first derived using standard dynamic programming utilizing the neighborhood concept of Brodie and Kao (1979). The state variables are stand volume, the number of trees and species composition (birch percentage of volume). The computation intervals, which also show the accuracy of determining the optimal solution, are 5 years, 20 m^3/ha (286 cu.ft./ac) for stand volume, 75 trees per hectare (30 trees per acre), and 5 % for species composition. The problem formulation and solution procedure is similar to the one described in detail in Valsta (1986).

The state space of a dynamic programming network expands rapidly when additional tree species are included in the analysis. To explore potentially more efficient solution procedures, direct search with the method of Hooke and Jeeves (see e.g. Bazaraa and Shetty 1979) is also applied. A computer program given in Osyczka (1984) was adapted to the present problem.

Corresponding to Roise (1986) the problem of finding the optimal rotation and thinnings is formulated as a nonlinear programming problem:

$$\max\ z = g(t_j, u_{ij}, t_{m+1}) \qquad i = 1,\ldots,n, \quad j = 1,\ldots,m \qquad (5)$$

subject to

$$\begin{aligned}
&\boldsymbol{x}_{j+1} = f(t_j, \boldsymbol{x}_j, \boldsymbol{u}_j, t_{j+1}) && j = 1,\ldots,m && (6)\\
&\boldsymbol{0} \leq \boldsymbol{u}_j \leq \boldsymbol{1} && \forall\ j && (7)\\
&t_j, x_{ij}, u_{ij} \geq 0 && \forall\ i, j && (8)\\
&\boldsymbol{x}_0 \quad \text{given} && && (9)
\end{aligned}$$

where

$g(\cdot)$ = the function for the optimum value of a cutting regime,
t_j = the time between thinning j-1 and j,
t_{m+1} = the time between the last thinning and the final harvest,
u_{ij} = the percentage of trees removed of species i in thinning j,
$f(\cdot)$ = the stand development model,
$\boldsymbol{x}_j$ = the vector of stand characteristics at cutting j,
$\boldsymbol{x}_0$ = the initial stand,
i = the index of tree species,
j = the index of thinning.

With a nondifferential optimization method, such as the Hooke and Jeeves' method, the stand dynamics (equation 6) may be excluded from the formulation. The problem now becomes an unconstrained nonlinear programming problem with upper and lower bounds for the variables u_{ij}. The objective function may be rewritten as:

$$\max\ z = g(t_j, u_{ij}, t_{m+1} \mid \boldsymbol{x}_0) \qquad i = 1,\ldots,n, \quad j = 1,\ldots,m \qquad (10)$$

subject to (7) and the nonnegativity restrictions. When the problem is solved the algorithm computes repeated values of equation (10) in which the stand dynamics are implicitely included. The value of equation (10) may thus result from any kind of deterministic relationship with the arguments.

RESULTS

In the growth model applied the species composition with fastest growth depends both on stand age and growing stock level. Adjusting the species composition means reducing the growing stock. Hence there is no simple rule we could follow in order to maximize volume growth over the rotation. In addition, the solution always depends on the initial condition, i.e. the regeneration result.

The initial stand in the analysis is a 30-year-old even-aged stand with a growing stock of 100 m^3/ha (1400 cu.ft./ac) and 1200 trees per hectare (480 trees per acre). The species composition is allowed to vary freely and it is also assumed that any mixture could have been generated with the same cost and would have an equal growing stock at age 30.

When maximizing mean annual increment (M.A.I.) the optimal growing stock consists mostly of spruce (Figure 1), especially towards the end of rotation. The proportion of birch first slowly increases due to the more rapid growth of birch.

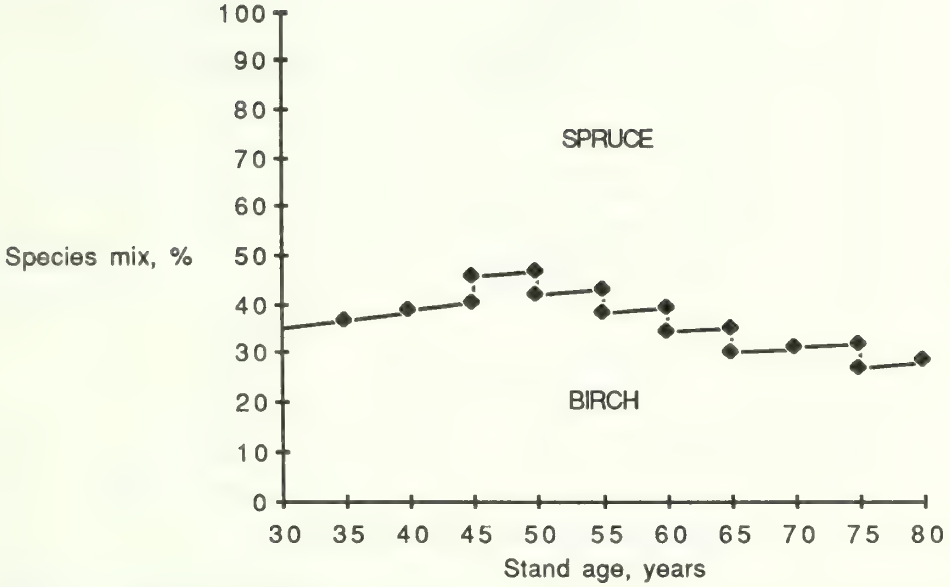

Figure 1. The optimal species composition (per cent of stand volume) when maximizing mean annual increment.

In the first thinning at age 45 the proportion of birch is increased slightly. This seems to be an anomaly caused by the minimum of 5 % steps in species composition of the initial stand. Later, the proportion of birch is decreased as its growth is declining faster with increasing age. The M.A.I. of the optimal mixture was 9 % higher than that of the pure spruce stand. The results are in agreement with the values reported by Mielikäinen (1985). With a fixed 25 % birch mixture he found a 6 % increase in M.A.I. over the pure spruce stand. Agestam (1985) found that the growth of the mixed stand was sometimes higher, sometimes lower than that of the pure spruce stand. However, the species compositions used in the simulations were suboptimal in view of the results from the present study.

The magnitude of the so called mixture effect resulting from different species compositions may be seen in Figure 2. The data points are generated by optimum thinning regimes with 0, 10, 20,..., 90, 100 % birch in the initial stand. Growth above the straight line is considered a result of the mixture effect.

The financially optimal species composition starts with a larger proportion of birch at the beginning of rotation (Figure 3). Later, birch is thinned heavily and a stand close to a pure spruce stand is final harvested. Two thinnings are made, the first one to avoid growth reduction due to overdensity and the second one to adjust species composition and to reduce the growing stock in order to maintain the relative value growth corresponding the interest rate. The soil expectation value of the mixed stand is 25 % higher than that of the spruce stand and 9 % higher than that of the birch stand.

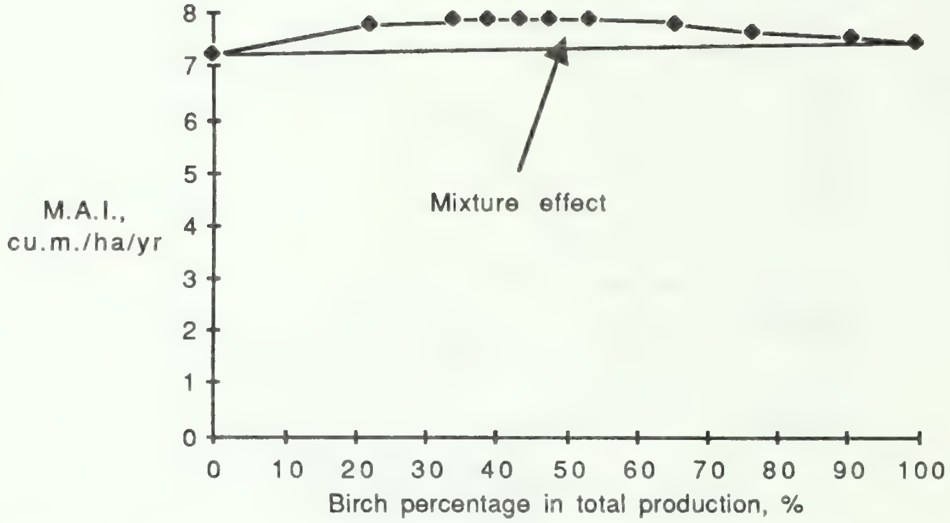

Figure 2. The maximum M.A.I. in relation to species composition of the total volume production during the rotation.

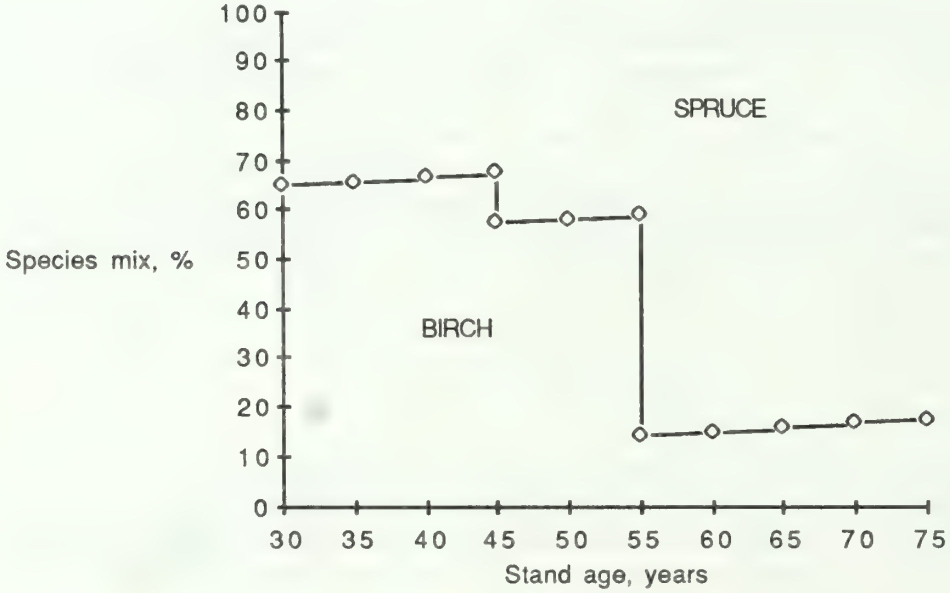

Figure 3. The optimal species composition (per cent of stand volume) when maximizing soil expectation value with 3 % interest rate.

A comparison of optimal solutions found with dynamic programming and the Hooke and Jeeves' direct search method is seen in Figure 4. The small differences between the solutions may be attributed to the 5 year–5 % state intervals used in dynamic programming. The optimal soil expectation values differ by 2 %, in favor of the Hooke and Jeeves' method. Equally consistent results are obtained when maximizing mean annual increment.

The optimal solution reported by the Hooke and Jeeves' method has an M.A.I. value 0.4 % higher than the one given by dynamic programming.

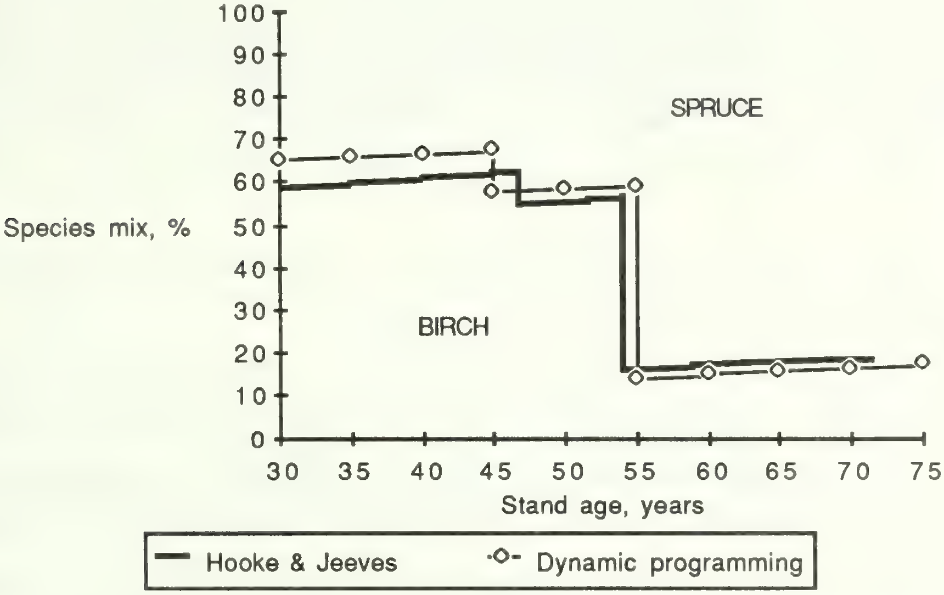

Figure 4. The optimal species composition for soil expectation maximization determined by (1) the method of Hooke and Jeeves and (2) dynamic programming.

When applied to the present optimization problem the version of the Hooke and Jeeves' method used suffered from slow convergence close to the optimum solution. Local optima were another problem. A local optimum exists for each number of thinnings (when a financial objective is used) and several local optima were identified also within a given number of thinnings. In practice, repeated computer runs were executed to arrive at a solution that was regarded as satisfactory. Two random search phases incorporated in the computer program by Osyczka (1984) were found useful. The first one generates a number of random starting points (e.g. 100) of which the best is taken as the initial solution. The other random search part is executed after a local optimum solution is found in order to locate any better solutions in the neighborhood of the present solution.

CONCLUSIONS

The problem of determining the optimum species composition, thinnings and rotation in a mixed, even-aged stand was solved using dynamic programming and direct search. The results obtained are specific to the initial state of the stand and, hence, no exact management guidelines can be stated for the type of forest analyzed. A whole-stand growth model was used in the analysis. Consequently, the results are applicable only to a fairly restricted group of stands that correspond to the growth model. The single-tree growth models, also reported by Mielikäinen (1985), have the potential of describing a wider range of stand types.

When the mixed stand with the optimum species composition was compared with pure stands of each species it was found superior for both volume production and soil expectation value maximization. The financial comparison is strongly dependent on the stumpage prices applied. In this study typical historical prices for the appropriate area were used.

Dynamic programming and direct search with the method of Hooke and Jeeves gave parallel results, as regards optimum solutions and objective function values. The differences between objective function values given by the two methods were considerably smaller than those reported by Roise (1986). Dynamic programming suffers from excessive computational load when several state variables are introduced. Using the approach presented by Paredes V. and Brodie (1987) this problem may be resolved in a part of analysis situations and a method finding a globally optimal solution may still be used.

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SIMULATED APPLICATIONS OF EMPIRICAL TIMBER PRODUCTIVITY EQUATIONS FOR FOREST SOILS IN SOUTHEASTERN ALASKA

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ABSTRACT. The use of timber productivity equations developed for five tree species on seven forest ecosystem soils is examined. A projection approach uses regional, species-specific stand tables to evaluate sites for future management actions such as maintaining current species, converting to other species, and changing stocking of chosen species.

INTRODUCTION

Forest managers need information, methods, or materials to help them accurately and efficiently direct the course of proposed management programs. These managers, when developing management plans, often strive to optimize the production or availability of one or more forest resources. Management planning to meet such objectives must be multi-faceted and is not generally limited to one item of analysis for decision processing.

Many factors come into play in developing effective forest resource management plans. Some of these factors are, by their nature, fixed and not amenable to change by the resource manager, but they are no less important in management planning than factors subject to management. Examples of fixed factors are climate and site characteristics such as aspect, slope, and soil. The more malleable factors include stand density, species composition, and tree size distributions.

The fixed and variable factors pertinent to management planning are interactive. Just as a manager striving for optimum production would not attempt to plant a tropical hardwood in a boreal setting, so should he or she consider effects of such site characteristics as soil on the optimum combination of variable factors. On a given soil, certain species grow better than others, and the degree to which a manager should favor one species over another may be a function of stand density. Reducing stocking may increase productivity of one species but not another. A change in stocking could change productivity levels to the degree that another species would be selected over a previously favored one for future management.

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I examined the relationship of individual tree growth to the soil on which the tree was growing (manuscript in preparation). Regression equations were developed for up to five tree species on seven ecosystem soils. The equations related periodic annual tree volume growth percent to the reciprocals of diameter at breast height (DBH), DBH squared, and percentage of live tree stocking (LTS). LTS is a measure of the growing space available to individual trees, expressed in basal area per acre. Analysis of covariance indicated measurable differences in tree growth both within and between species and soil groups.

This paper presents examples of how tree-growth equations specific to a particular species and soil can be used to evaluate management options.

METHODS

Data for developing the equations were from permanent, 10-point, variable-radius (basal area-factor = 62.5), forest-inventory sample plots established in southeastern Alaska. Data recorded on the plots included DBH, 10-year diameter increment, tree height, and a description of the forest-ecosystem soil.

Regression analyses were performed for five tree species on seven soils to relate periodic annual cubic-foot volume growth percent to tree DBH and percentage of LTS on the site. The tree species were Alaska-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), mountain hemlock (*T. mertensiana* (Bong.) Carr.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and western redcedar (*Thuja plicata* Donn). Tree stocking on the site was determined by ALCAL[1], computer software developed to compile Alaskan forest-inventory sample data. The soils are those characterized by Stephens and others[2] (1969) for the Tongass National Forest (Table 1). Periodic annual cubic-foot volume growth percent was established through use of 10-year diameter increment. Average annual increment, as estimated from the increment core, was subtracted from current diameter to estimate tree diameter 1 year before inventory. The two diameters and an estimate of height change were needed to establish tree volume at the two times. Volume growth percent was estimated by use of the two volumes and their difference.

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[1] The ALCAL program is on file at the Forestry Sciences Laboratory, USDA Forest Service, 201 East 9th Avenue, Suite 303, Anchorage, Alaska 99501.

[2] Stephens, F. R.; C. R. Gass; R. F. Billings; and D. E. Paulson. 1969. Soils and associated ecosystems of the Tongass. (Draft). USDA Forest Service, Juneau, Ak.

TABLE 1. General characteristics of southeastern Alaska forest soils.

Forest ecosystem [1]	Drainage	Depth	Texture
F1	Well drained	> 10 inches mineral soil over bedrock	Sandy loam to silt loam
F2	Freely drained	< 12 inches, shallow to bedrock	Peat over gravelly loam
F2r	Well drained	Duff over gravel bedrock	Undecomposed litter over gravelly silt loam
F4	Somewhat poor	> 30 inches, generally	Sandy loam to silt loam to gravelly silt loam
F5	Poor	> 24 inches	Black muck to mucky peat
F6	Somewhat poor	Shallow to bedrock	Stony
f1	Well drained	> 36 inches	Silt loam to very fine sandy loam

[1] "F" ecosystems-have mature soils; "f" ecosystems-have relatively fast rates of soil development. Source: Stephens, F. R.; C. R. Gass; R. F. Billings; and D. E. Paulson. 1969. Soils and associated ecosystems of the Tongass. (Draft). USDA Forest Service, Juneau, Ak.

Regression equations were developed for each tree species and soil combination for which 30 or more observations of tree growth percent were available. Analyses of covariance were performed on equations within and between forest-ecosystem categories. With the exception of Alaska-cedar, mountain hemlock, and western hemlock on F2r soils, and Alaska-cedar and western hemlock on F5 soils, all equations were significantly different from each other. For those that were not, data were pooled and a combined equation was developed.

The approach to evaluating management options was to "grow" a stand of trees, tree by tree, for 1 year using the growth rates predicted by the equations developed earlier. A table of average volumes per tree by 2-inch DBH class and species was then used to determine if the new tree volume was in the next higher DBH class. If the new volume was in the next DBH class, the growth rate appropriate to that class was applied to the new volume; otherwise, the former growth rate was applied. In this manner, the trees were grown for 15 years. Stand volume per acre was obtained by multiplying the number of trees in the diameter class by the ending volume per tree and summing over all diameter classes. Demonstrating all of the equations developed earlier is beyond the scope of this paper. Equations for western hemlock and Sitka spruce growing on F1 and F5 soils were used as examples (Table 2).

TABLE 2. Equations for periodic annual cubic-foot tree-volume growth percent for western hemlock and Sitka spruce on F1 and F5 soils in southeastern Alaska.

F1 soil

Western hemlock

$$Pv = -.308 + 108.005\ (1/LTS) - 8635.503\ (1/LTS^2) + 535.278\ (1/DBH^2)$$

Sitka spruce

$$Pv = -.008 + 64.705\ (1/LTS) - 1977.936\ (1/LTS^2) + 461.279\ (1/DBH^2)$$

F5 soil

Western hemlock

$$Pv = -.487 + 74.072\ (1/LTS) - 3008.739\ (1/LTS^2) + 178.035\ (1/DBH^2)$$

Sitka spruce

$$Pv = -.251 + 159.392\ (1/LTS) - 8020.865\ (1/LTS^2) + 98.981\ (1/DBH^2)$$

Where: Pv = annual percent tree-volume growth;
LTS = percentage of live tree stocking; and
DBH = tree diameter at breast height.

To demonstrate evaluation of management options, the likely future productivity of the existing stand served as the basis for comparison. In this study, the "existing" stand was a composite of all poletimber plots on the F1 soils in the Prince of Wales inventory unit of southeastern Alaska. This "composite" plot was used as the basis for growth projections of both western hemlock and Sitka spruce. Only trees $\geq$ 5.0 inches DBH were used because this is the size used in developing the equations. Stand characteristics--such as number of trees per acre, percentage of LTS, and diameter distributions--were those estimated by the 10-point samples. Thus, the "stand" does not have a real area, and all computations are on a per-acre basis. Volumes per tree are averages, by species, across the entire Prince of Wales unit. For comparability, the same distribution of number of trees by diameter class was maintained for each stand, along with the same LTS and beginning volume per tree by species for the stands growing on F5 soils. See Table 3 for basic "stand" structure.

Changes in stand density were represented by varying the percentage of LTS. The initial value of 498 percent is that of the composite plot. Rather than change the beginning stand structure, stand-density reductions were conceptually accomplished by removing trees less than 5.0 inches in diameter.

Three management options for two species growing on the two soils mentioned above were examined. They are (1) to maintain existing stand conditions, (2) to maintain existing species but reduce the percentage of LTS per acre, and

TABLE 3. Initial stand conditions used to demonstrate use of equations for tree-volume growth (percentage of LTS = 498) on forest soils in southeastern Alaska.

Tree diameter (inches)	Number of trees per acre	Cubic-foot volume per tree	
		Sitka spruce	Western hemlock
6	74	1.99	2.24
8	39	5.28	4.72
10	34	9.61	10.57
12	8	22.13	20.08
14	3	34.98	31.02
16	5	47.47	45.74
18	2	64.42	62.96
20	0	0	0
22	0	0	0
24	1	130.11	125.29

(3) to convert to a stand of similar structure with another species.

RESULTS

Western hemlock grown for 15 years on the F1 soils exhibited a gross cubic-foot volume increase of 1,624.5 cubic feet over the beginning volume of 1442.9 cubic feet (Table 4), 126 percent of the beginning volume. Reduction of LTS to 100 percent, from the beginning 498 percent, increased volume growth by 14.5 cubic feet to 1,639.0 cubic feet (Table 5). This increase is < 1 percent higher than the volume growth under the overstocked condition.

Absolute volume growth of Sitka spruce grown on the F1 soils was not as great as that of western hemlock (Table 4). In 15 years, spruce growth in the overstocked conditions (LTS = 498 percent) was 1,443.8 cubic feet (an increase of 99 percent over the beginning volume of 1,458.1 cubic feet). Reduction of LTS to 100 percent increased volume growth by 90.3 cubic feet to 1,534.1 cubic feet (Table 4). This volume growth is 6.25 percent higher than under the overstocked conditions.

On the F5 soils, assuming the same initial stand volume and LTS of 498 percent, western hemlock grew 371.9 cubic feet under the overstocked conditions, an increase of 25.8 percent (Table 4). At 100-percent LTS, western hemlock growth (452.1 cubic feet) increased 80.2 cubic feet to 1,895.1 cubic feet, an increase of 5.5 percent in volume growth (Table 5).

Table 4. Initial (V1) and projected (V2) 15-year cubic-foot volumes/acre by forest soil, tree species, and initial diameter at breast height (percentage live-tree stocking = 498).

	F1 Soil				F5 Soil			
	Sitka spruce		Western hemlock		Sitka spruce		Western hemlock	
DBH	V1	V2	V1	V2	V1	V2	V1	V2
	cubic feet							
6	147.3	671.9	165.8	771.1	147.3	222.5	165.8	325.4
8	205.9	513.2	184.1	538.6	205.9	260.5	184.1	263.9
10	326.7	653.5	359.4	748.3	326.7	381.0	359.4	444.7
12	177.0	288.9	160.6	267.4	177.0	197.1	160.6	183.5
14	104.9	149.7	93.1	136.7	104.9	113.8	93.1	101.2
16	237.4	315.7	228.7	306.0	237.4	252.7	228.7	241.0
18	128.8	159.9	125.9	158.1	128.8	135.6	125.9	129.8
20	--	--	--	--	--	--	--	--
22	--	--	--	--	--	--	--	--
24	130.1	149.1	125.3	141.2	130.1	134.3	125.3	125.3
Total	1458.1	2901.9	1442.9	3067.4	1458.1	1697.5	1442.9	1814.8

Table 5. Initial (V1) and projected (V2) 15-year cubic-foot volumes/acre by forest soil, tree species, and initial diameter at breast height (percentage of live-tree stocking = 100).

	F1 Ecosystem				F5 Ecosystem			
	Sitka spruce		Western hemlock		Sitka spruce		Western hemlock	
DBH	V1	V2	V1	V2	V1	V2	V1	V2
	cubic feet							
6	147.3	667.5	165.8	774.0	147.3	239.3	165.8	339.2
8	205.9	536.6	184.1	541.7	205.9	280.4	184.1	275.7
10	326.7	684.1	359.4	751.4	326.7	410.3	359.4	464.8
12	177.0	297.8	160.6	269.0	177.0	212.4	160.6	191.8
14	104.9	156.0	93.1	137.6	104.9	122.7	93.1	105.8
16	237.4	329.7	228.7	307.4	237.4	272.3	228.7	251.7
18	128.8	166.7	125.9	158.8	128.8	146.3	125.9	135.7
20	--	--	--	--	--	--	--	--
22	--	--	--	--	--	--	--	--
24	130.1	153.8	125.3	142.0	130.1	144.7	125.3	130.3
Total	1458.1	2992.2	1442.9	3081.9	1458.1	1828.4	1442.9	1895.0

Sitka spruce growing on the F5 soils showed dramatic response to changes in stocking. At high stocking, volume growth was 239.4 cubic feet, from a beginning volume of 1,458.1 cubic feet to a volume 15 years later of 1,697.5 cubic feet (Table 4), an increase of 16.4 percent of beginning volume. Reduction of LTS to 100 percent produced a final volume of 1,828.4 cubic feet (Table 5), an increase of 370.21 cubic feet (25.4 percent of starting volume). The percentage increase in volume growth was 9.0.

DISCUSSION

On F1 soils, if the existing stand was composed of western hemlock, the likely choice among the three management options would be to maintain existing conditions. Reducing stocking did not raise growth to a rate likely to offset costs of reduction. Conversion to Sitka spruce would apparently not be advisable because growth would be reduced no matter what the stocking was.

If, on F1 soils, the initial stand were composed of Sitka spruce, the choice would depend on the relative market values of the two species. Reducing stocking has a more dramatic effect on the spruce stand than on the western hemlock stand and may be economically worthwhile. If, however, the western hemlock is more valuable than the Sitka spruce, species conversion combined with stocking reduction may be worthwhile.

If the initial stand on the F5 soils was western hemlock, the only option perhaps worth considering is reducing stocking. Growth increased nearly 6 percent when stocking was reduced, and this increase may be worth the investment in thinning. Species conversion would not be an option because even at low stocking Sitka spruce growth was low.

Sitka Spruce growing on F5 soils exhibited the most dramatic response to stocking reduction of the four examples. An increase of nearly 9 percent in growth makes stocking reduction an attractive option if the manager wishes to retain Sitka spruce on the site. Converting to western hemlock is also possible but would depend on the value of the two species because the gain in growth is not as substantial as that produced by stocking reduction.

The examples above present a simplified approach to growth projection and comparisons. Different stands would likely have different diameter distributions and may be of mixed species; these situations are also easily compared. Fine-tuning the diameter-class resolution would more accurately estimate growth but would likely show similar trends. Stocking reductions could realistically occur in all diameter classes, not just in those less than 5.0 inches. Also, soil productivity could be enhanced through site improvements such as better drainage on wet soils.

These growth equations were developed specific to a particular species and soil; they can, in turn, be used as part of a larger, more comprehensive, modelling procedure to compare management options.

A STAND GROWTH MODEL FOR YIELD REGULATION IN NORTH QUEENSLAND RAINFORESTS

Jerome K. Vanclay[1]

ABSTRACT. A stand growth model used to predict timber yields from north Queensland's rainforests is described. Some 150 commercial and 750 other tree species are aggregated into about twenty species groups based on growth habit, volume relationships and harvesting practices. Trees are grouped according to species group and tree size into cohorts, which form the basis for simulation. Equations to predict increment, mortality and recruitment were derived through linear regression.

INTRODUCTION

The tropical rainforests of Queensland have been managed for timber production since early this century. The total area of rainforest north of Townsville (19°S, Figure 1) is 860 000 hectares, of which 160 000 hectares (nett) are managed for sustained timber production. About 900 tree species have been described from these forests, of which over 150 are of commercial interest. These include many fine cabinet timbers such as red cedar (*Toona australis*) and northern silky oak (*Cardwellia sublimis*). A growth model has been developed to enable the sustained yield of these forests to be calculated.

MODEL STRUCTURE

To satisfy the requirements of yield regulation, a growth simulator should be:

- a stand growth model which predicts annual growth;
- deterministic to enable efficient yield forecasting;
- modular to simplify alterations and enhancements;
- flexible enough to utilize various inventory data;
- useful for investigating alternative logging strategies.

Several models have been constructed to examine ecological succession in various forest types (e.g. Shugart, 1984), but these are generally unsuited to yield regulation applications. Transition matrix approaches (Usher, 1966) are an efficient method of summarizing data, but contribute little towards an understanding of the processes of growth within the forest. Individual tree models pose difficulties in accurately and deterministically forecasting mortality.

The U.S. Forest Service (1979) developed a more flexible approach for temperate mixed species forests in the Great Lakes region, but took no account of regeneration and recruitment. Vanclay (1985) presented a model for monospecific stands of *Callitris glaucophylla* which can readily be modified to suit the demands of mixed species stands. The key feature of this approach is to identify *cohorts* (Reed, 1980), groups of individual trees which may be assumed to exhibit similar growth and which may be treated as single entities within the model. Cohorts are formed by grouping trees according to species affiliation and stem size, and need not contain equal numbers, or whole numbers of stems.

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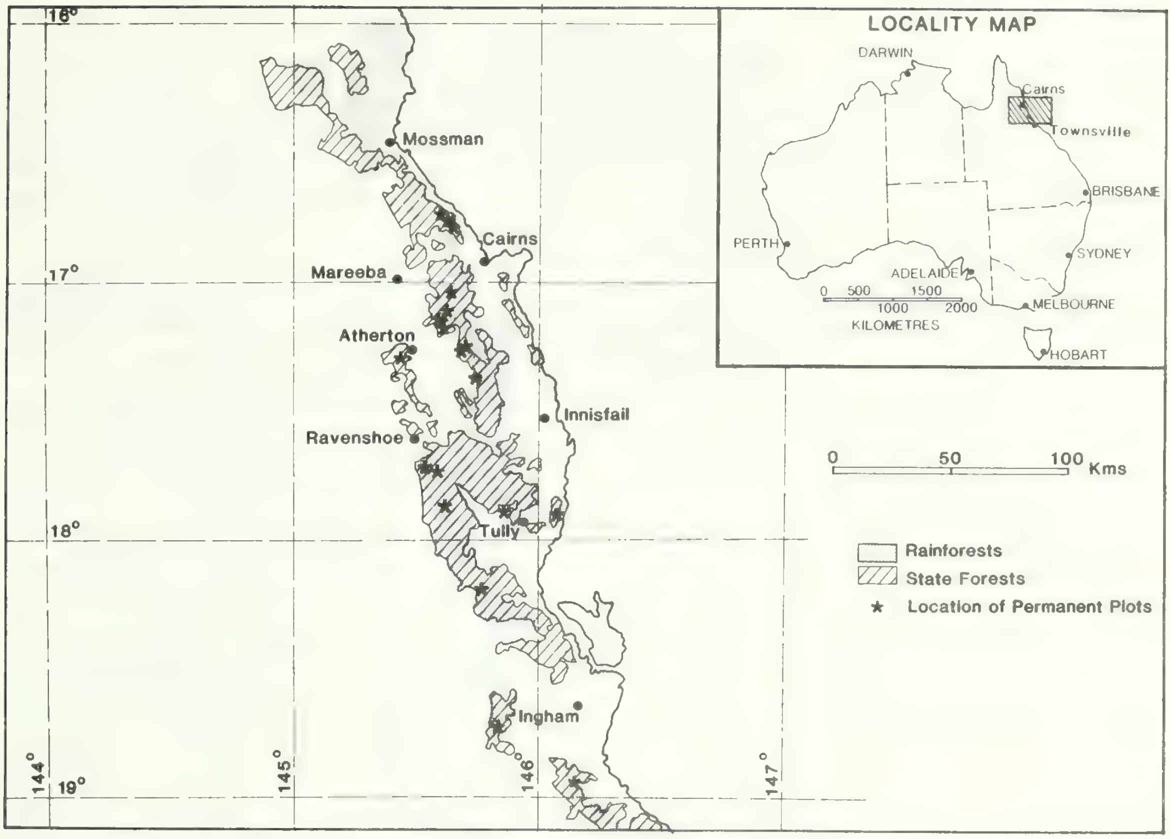

FIGURE 1. LOCATION OF STUDY AREA

The rainforest growth model admits a maximum of 200 cohorts for each stand. Initially, stems from the same species group and whose diameters differ by less than five millimetres are grouped into a single cohort. If necessary, greater differences are accommodated by forming groups of stems most similar in size.

During simulation, cohorts comprising more than a critical number of stems or exhibiting diameter increments exceeding five millimetres per annum may split into two new cohorts, one with 25% of the stems and 1.3 times the predicted current annual increment, and one with 75% of the stems and 0.9 times the predicted current annual increment. This reflects the skewed nature of increment commonly observed in rainforest stands (Bragg and Henry, 1985). The critical number of stems varies with stem size, and is twenty stems per hectare for stems below 40 cm dbh (diameter at breast height, over bark), five stems per hectare for stems exceeding 40 cm dbh, and two stems per hectare for stems exceeding the normal merchantable size (50 to 100 cm diameter breast height or above buttressing depending upon species). The total number of cohorts is maintained below 200 by merging, within species groups, cohorts with the most similar diameters.

DATA SOURCES

Thirty seven permanent plots, varying in size from 0.1 to 0.4 hectares and representing over two hundred thousand tree years of measurement were used in developing the model. These plots sample both virgin and logged rainforest on a variety of forest and soil types (Figure 1).

Data recorded include species identity, merchantability, measurements of dbh, details of soils and geology, and a good/poor site assessment based on soil parent material, standing volume, average log length and species present.

TABLE 1. Composition of Growth Groups

Group 1 (Large, Fast growing)	Group 2 (Large, Slow growing)	Group 3 (Small, Fast growing)	Group 4 (Small, Slow growing)
Acmenosperma claviflorum	*Ackama australiana*	*Acacia aulacocarpa*	*Acmena divaricata*
Agathis atropurpurea	*Acmena resa*	*Acacia crassicarpa*	*Acmena graveolens*
Agathis microstachya	*Backhousia bancroftii*	*Acacia implexa*	*Acmena smithii*
Agathis robusta	*Backhousia hughesii*	*Acacia mangium*	*Ailanthus triphysa*
Albizia toona	*Beilschmiedia bancroftii*	*Acacia melanoxylon*	*Alstonia muellerana*
Alstonia actinophylla	*Beilschmiedia* sp.	*Albizia xanthoxylon*	*Alstonia spectabilis*
Alstonia scholaris	*Blepharocarya involucrigera*	*Alpitonia petriei*	*Archidendron vaillantii*
Argyrodendron peralatum	*Cardwellia sublimis*	*Barringtonia asiatica*	*Argyrodendron polyandrum*
Elaeocarpus grandis	*Castanospermum australe*	*Barringtonia calyptrata*	*Argyrodendron trifoliolatum*
Endiandra palmerstonii	*Ceratopetalum succirubrum*	*Barringtonia racemosa*	*Cryptocarya erythroxylon*
Eucalyptus grandis	*Cinnamomum oliveri*	*Callitris macleayana*	*Cryptocarya rigida*
Flindersia brayleyana	*Dysoxylum cerebriforme*	*Cinnamomum laubatii*	*Darlingia darlingiana*
Flindersia ifflaiana	*Dysoxylum fraseranum*	*Cryptocarya oblata*	*Dysoxylum oppositifolium*
Flindersia pimenteliana	*Dysoxylum micranthum*	*Daphnandra repandula*	*Elaeocarpus foveolatus*
Palaquium galactoxylum	*Dysoxylum muelleri*	*Darlingia ferruginea*	*Endiandra cowleyana*
Prumnopitys amara	*Dysoxylum pettigrewianum*	*Doryphora aromatica*	*Endiandra hypotephra*
Syzygium claviflorum	*Elaeocarpus coorangooloo*	*Elaeocarpus largiflorens*	*Endospermum myrmecophilum*
Syzygium gustavioides	*Elaeocarpus ruminatus*	*Elaeocarpus sericopetalus*	*Endospermum peltatum*
Toona australis	*Endiandra acuminata*	*Eucalyptus tereticornis*	*Eucalyptus drepanophylla*
Wrightia laevis	*Endiandra dichrophylla*	*Eucalyptus torelliana*	*Eucalyptus siderophloia*
	Endiandra glauca	*Eucalyptus resinifera*	*Intsia bijuga*
	Endiandra montana	*Eucalyptus pellita*	*Nauclea orientalis*
	Endiandra tooram	*Euodia bonwickii*	*Neonauclea gordoniana*
	Flindersia laevicarpa	*Euodia elleryana*	*Oreocallis wickhamii*
	Galbulimima belgraveana	*Euodia vitiflora*	*Orites racemosa*
	Geissois biagiana	*Euodia xanthoxyloides*	*Planchonella arnhemica*
	Gmelina dalrympleana	*Flindersia acuminata*	*Planchonella obovata*
	Gmelina fasciculiflora	*Flindersia bourjotiana*	*Planchonella obovoidea*
	Gmelina leichardtii	*Gevuina bleasdalei*	*Planchonella pohlmaniana*
	Metrosideros queenslandica	*Litsea bindoniana*	*Pleiogynium timorense*
	Musgravea heterophylla	*Litsea glutinosa*	*Polyalthia michaelii*
	Musgravea stenostachya	*Litsea leefeana*	*Pseudoweinmannia lachnocarpa*
	Neorites kevediana	*Litsea reticulata*	*Ristantia pachysperma*
	Ormosia ormondii	*Melaleuca argentea*	*Schizomeria ovata*
	Syncarpia glomulifera	*Melaleuca leucadendra*	*Schizomeria whitei*
	Syzygium luehmannii	*Melaleuca quinquenervia*	*Sloanea australis*
	Syzygium wesa	*Melaleuca viridiflora*	*Symplocos stawellii*
	Xanthostemon whitei	*Melia azedarach*	*Synoum muelleri*
		Myristica muelleri	*Syzygium dictyophlebium*
		Opistheolepis heterophylla	*Syzygium kuranda*
		Placospermum coriaceum	*Syzygium luehmannii*
		Podocarpus elatus	*Syzygium paniculatum*
		Prumnopitys ladei	*Syzygium papyraceum*
		Prunus turnerana	*Syzygium trachyphloia*
		Sloanea langii	*Syzygium wilsonii*
		Sloanea macbrydei	
		Terminalia sericocarpa	

SPECIES GROUPS

Because of the large numbers of tree species represented in tropical rainforests, it is clearly impractical to develop separate functional relationships for each tree species. To sensibly aggregate these species, it is expedient to employ three criteria, namely the volume relationship, logging practice and growth pattern. In the model, species groups are identified by a four digit code, SVLG, where S represents the datum source (0 = inventory, 1 = predicted ingrowth), V indicates the volume equation to be used (1 to 4), L indicates the logging rule applicable (1 to 9 inclusive) and G indicates the growth group. Five growth groups were identified on the basis of merchantability, size commonly attained and growth rate. The composition of the four commercial groups is indicated in Table 1, and the fifth group comprises all remaining tree species. Practical necessity required the use of a single group for all non-commercial species, as inventory identified only commercial and potentially commercial species, with most non-commercial species recorded as miscellaneous. Generally, group 1 contains gap opportunists, group 3 contains other pioneer and short-lived species, and groups 2 and 4 contain shade tolerant species.

DIAMETER INCREMENT

To ensure reliable forecasts despite often quite variable data, a diameter increment function was devised which ensured a predicted growth pattern similar to that observed, would be sensitive to site and stand conditions, and could be readily established using linear regression. This function has the form

$$DI = (D_{\max} - D) \times D^{k} \times f\,(SBA, SQ, PM) \qquad (1)$$

where DI is the dbh increment (cm/ann), D is the dbh (cm), $D_{\max}$ is the maximum attainable diameter, k is a parameter to be estimated, and $f\,(SBA, SQ, PM)$ is a linear expression in stand basal area, site quality and soil parent material.

It is appropriate to constrain the increment function by identifying the maximum attainable diameter ($D_{\max}$) which a given species on a nominated site can barely attain. This can be estimated using statistical analyses where sufficient data are available. However, in rainforests (even virgin stands), very large stems occur infrequently, and few data exist for these stems. Thus it is expedient to determine the $D_{\max}$ subjectively for each growth group and soil parent material, based on available data and local knowledge.

The predicted growth pattern is determined largely by the parameter k in Equation 1. Graphical analysis revealed that for most groups a value of 0.667 appeared to be appropriate. Statistical analysis confirmed that for groups 1, 2 and 5 on all sites, the estimated values were very close to, and not significantly ($P<0.05$) different from 0.667, which was consequently adopted. Slightly different values were obtained for growth groups 3 and 4.

Because of the vast amount of data, the disproportionate representation of smaller size classes, and to facilitate graphical analyses of the residuals, the data were grouped according to site quality, soil parent material, stand basal area and 5 cm dbh classes. Some cells were further grouped to enable the estimation of the variance within each cell. The mean dbh and stand basal area of each cell were used in the analysis, and site quality and soil parent material were included as dummy (0, 1) variables. Linear regression, weighted by the inverse of the variance, produced the following results (all parameters are significant at $P<0.05$ or better throughout the paper):

$$DI_1 = (140 - 20\,TG - D) \times D^{0.667} \times (2.497 + 1.196\,SQ - 1.061\,BV - 0.02859\,SBA) \times 10^{-4}$$

$$DI_2 = (160 - 30\,TG - D) \times D^{0.667} \times (2.543 + 0.2737\,CG - 0.02902\,SBA) \times 10^{-4}$$

$$DI_3 = (120 - D) \times D^{0.765 - 0.051\,TG} \times (2.478 + 1.055\,SQ - 0.8328\,CG - 0.03364\,SBA) \times 10^{-4}$$

$$DI_4 = (110 - D) \times D^{0.833 + 0.013\,TG} \times (1.542 + 0.3924\,CG - 0.01741\,SBA) \times 10^{-4}$$

$$DI_5 = (170 - 40\,SA - 60\,TG - D) \times D^{0.667} \times (2.076 - 0.3831\,CG - 0.01894\,SBA) \times 10^{-4}$$

where DI_i is the dbh increment (cm/ann) of growth group i, D is dbh (cm), SBA is stand basal area (m^2/ha of stems exceeding 20 cm dbh), SQ is 1 for good sites and 0 for poor sites, BV is 1 on Basic Volcanic parent material, CG is 1 on Coarse Granite parent material, SA is 1 on Sedimentary, Metamorphic and Acid Volcanic parent material, and TG is 1 on Tully Granite parent material. The strong interaction of soil parent material on the growth pattern of species groups (Figure 2) is consistent with earlier observations (Nicholson *et al.*, 1983).

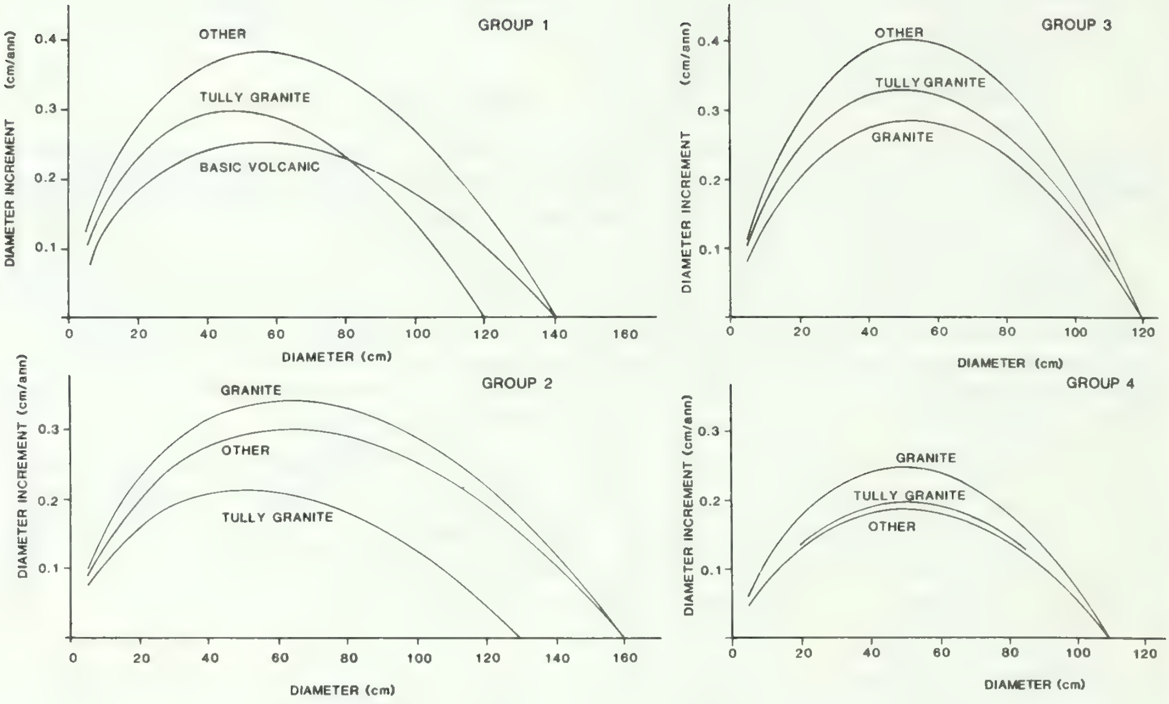

FIGURE 2. DIAMETER INCREMENT FUNCTIONS
(ASSUMING 20 m^2/ha BASAL AREA AND GOOD SITE)

MORTALITY

Several approaches to predicting mortality have been described, but most have been developed for monospecific stands and are not suited for modelling rainforest stands. A suitable and robust approach is to predict mortality from tree size and stand density using a logistic function (Hamilton and Edwards, 1976). Linear regression was used to fit the following relationships:

$$P_1 = \left(1 + e^{5.899 - 6.039 D^{-1} - 0.008392 SBA}\right)^{-1}$$

$$P_2 = \left(1 + e^{4.379 + 0.1010 D - 0.0007908 D^2 - 0.01477 SBA}\right)^{-1}$$

$$P_3 = \left(1 + e^{5.261 - 5.838 D^{-1}}\right)^{-1}$$

$$P_4 = \left(1 + e^{5.331 - 2.802 D^{-1} - 0.004500 SBA}\right)^{-1}$$

$$P_5 = \left(1 + e^{4.894 - 1.764 D^{-1}}\right)^{-1}$$

where P_i is the annual probability of mortality within growth group i, D is dbh (cm) and SBA is stand basal area (m^2/ha of stems exceeding 20 cm dbh).

The trend in growth group 2 contrasts strongly to that of the other growth groups (Figure 3), but is not inconsistent with findings of other workers (e.g. Buchman *et al.*, 1983).

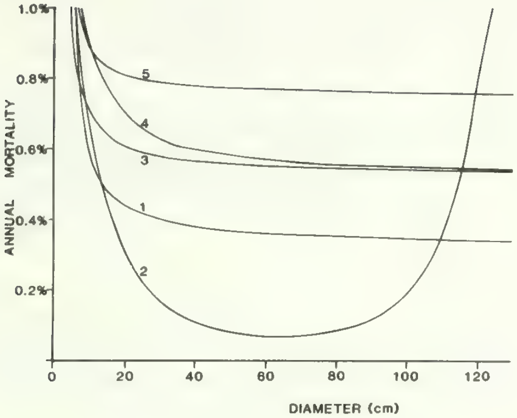

FIGURE 3. MORTALITY

(ASSUMING 20 m^2/ha BASAL AREA)

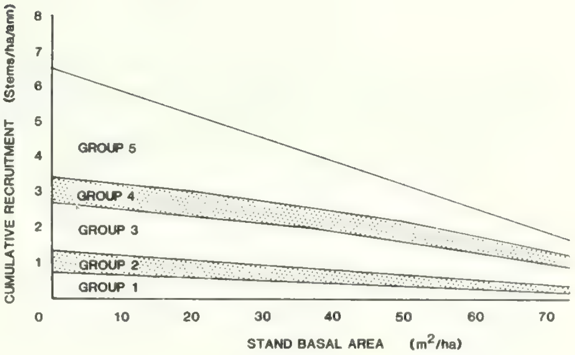

FIGURE 4. RECRUITMENT ON GOOD SITES

(ASSUMING 20m^2/ha BASAL AREA)

RECRUITMENT

The irregular nature of recruitment suggests a stochastic function, but efficient yield prediction requires a deterministic model. A robust approach is to predict the total recruitment, and apportion it amongst the species groups.

As the minimum stem size measured in inventory has varied between 3 and 20 cm dbh, recruitment must be predicted at 20 cm dbh. However, data concerning stems less than 20 cm dbh can be employed by marking the lower limit of measurement with a "ghost" stem in each growth group, and activating the prediction of recruitment for any growth group only when the marker (or ghost stem) attains 20 cm dbh.

Graphical inspection of the data suggested that recruitment at 20 cm dbh was linearly related to stand basal area and correlated with site quality. Total recruitment was predicted as

$$N = 5.466 - 0.06469\,SBA + 1.013\,SQ$$

where N is the number of recruits (*stems/ha/ann* at 20 cm dbh), SBA is stand basal area (m^2/ha of stems exceeding 20 cm dbh) and SQ is 1 on good sites and 0 on poor sites. On average, recruitment does not exceed 6.5 stems per hectare per annum, and does not occur where stand density exceeds 100 and 85 square metres per hectare basal area on good and poor sites respectively.

The proportion of recruitment in each growth group is predicted using a logistic function incorporating stand basal area, composition and site quality, but soil parent material was not significant. The use of the basal area of each growth group rather than the number of stems ensures robust predictions when inventory data derived from horizontal point sampling (probability proportional to size) are projected. The following relationships were derived by linear regression:

$$P_1 = 1 - \left(1 + e^{-2.407 - 0.005608\,SBA + 0.01105\,B_1 + 0.00464\,B_1 SQ}\right)^{-1}$$

$$P_2 = 1 - \left(1 + e^{-2.572 - 0.006756\,SBA + 0.11800\,B_2 - 0.06434\,B_2 SQ}\right)^{-1}$$

$$P_3 = 1 - \left(1 + e^{-1.761 - 0.008240\,SBA - 0.08076\,B_3 + 0.16610\,B_3 SQ}\right)^{-1}$$

$$P_4 = 1 - \left(1 + e^{-2.440 - 0.010690\,SBA + 0.16470\,B_4 - 0.06230\,B_4 SQ}\right)^{-1}$$

$$P_5 = 1 - \left(1 + e^{-0.655 - 0.024960\,SBA + 0.10630\,B_5 - 0.02621\,B_5 SQ}\right)^{-1}$$

where P_i is the proportion of the total recruitment as growth group i, SBA is stand basal area (m^2/ha of stems exceeding 20 cm dbh), B_i is the basal area of growth groups i, and SQ is 1 on good sites and 0 on poor sites. To ensure that these estimated proportions summed to exactly 1.0, the proportions were standardized:

$$P'_i = \frac{P_i}{\sum P}$$

Figure 4 illustrates how recruitment varies in response to changing stand density, assuming that stand composition is constant (each growth group comprising 20 percent of the stand basal area). Recruitment also varies in response to changing stand composition.

Once the growth groups have been resolved, the proportion of each growth group in any logging group is determined according to the composition of the corresponding stand fraction. The use of numbers of stems rather than basal area ensures reliable predictions despite the presence of useless veteran trees. Thus, for example, if it is determined that five percent of the growth group 1 stems in the existing stand are useless, then five percent of the predicted growth group 1 recruits will be assigned to that category. A similar procedure is followed to determine the volume group.

YIELD FORECASTS

The growth model is of course, but one small component of yield forecasting. Other components such as inventory data, area estimates, harvesting models and volume equations are equally important.

Area estimates for north Queensland rainforests were prepared from a database recording land tenure, forest type, accessibility and other management aspects at each intersection of the 1000 metre Australian Map Grid. Two-stage sampling was conducted to confirm this information, and to provide inventory data. In all, some 320 inventory plots, established over a seven year period, were used in the yield calculation. Inventory employed 1.0 ha and 0.5 ha rectangular plots, and clusters of ten point samples using 10 m^2/ha basal area factor optical wedges. A harvesting sub-model was used to predict removals during logging. Regional one-way volume equations were used.

Yield forecasts were prepared by simulating the growth of each individual plot to the middle of the next logging cycle, and using the harvesting sub-model to forecast the volume of removals. This process was repeated for subsequent logging cycles to ensure the continued yield. The sustained yield so determined was 60 000 cubic metres per annum, from a net resource area of 160 000 hectares. This is only 0.4 cubic metres per hectare per annum, a much lower yield than is generally assumed. The low yield may be attributed to the conservative selection logging system employed, to mortality, and to the high total biomass growth relative to the useful log volume increment.

CONCLUSION

This model has provided an objective basis for appraising management decisions, and for determining the sustainable yield of Queensland's northern rainforests.

Important advances include the identification of growth groups based on growth characteristics, the recognition of the influence of stand density on all aspects of stand dynamics, the explicit identification of a maximum attainable size, an attempt to quantify the site productivity (by site classification and identification of soil parent material), and the recognition that stand composition may influence the composition of recruitment. The advantage in recognizing a maximum attainable diameter is that it ensures that dbh increments cannot be overestimated for the larger trees being modelled, thus ensuring a very robust model. Prediction of recruitment at 20 cm dbh is less than desirable from a modelling viewpoint, but this is necessary to enable forecasts using all available inventory data.

Careful selection of component functions has ensured a robust model which provides realistic forecasts for a diverse range of forest types and inventory data. Standard analytical techniques including graphical inspection, weighted linear regression and inspection of residuals were used in developing the model.

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MODELING UNEVEN-AGED FOREST MANAGEMENT ON THE DESCHUTES NATIONAL FOREST

Mike Znerold 1/

ABSTRACT. During 1986 the Deschutes National Forest issued a draft Forest Plan and requested public comment. Sixty percent of the public who responded by letter opposed the practice of clearcutting as endorsed by the plan. As a result, the Forest chose to analyze the implications of uneven-aged management on timber yield and economic return. This analysis required development of uneven-aged yield tables which described the flow of timber yields during the 150 year planning horizon. The Prognosis growth and yield model was used to develop these yield tables. This exercise using actual stand data represented a new and untested application of Prognosis. After calibration and testing, the model performed satisfactorily and produced uneven-aged yield tables which were incorporated into the Forplan model. When constrained to use these yield tables on 153,000 acres of ponderosa pine and mixed conifer, the long run sustained yield and the present net value of the Forest dropped by four percent. This reduction was deemed acceptable by the Forest Management Team. As a result of this analysis, uneven-aged management will be strongly considered as a part of the management strategy in the final Forest Plan.

THE PUBLIC ISSUE

The Draft Forest Plan for the Deschutes National Forest was issued early in 1986. Over 1640 letters were received in reaction to the proposed plan. Of those responding, more than 60 percent expressed strong opposition to clearcutting. Few, if any comments were received in support of current timber harvest activities or those proposed in the Draft Plan. Activities on the Forest had focused largely on even-aged management. Clearcutting and shelterwood cutting had been the favored silvicultural systems applied. Less than five percent of the total harvestable acres were scheduled for uneven-aged management.

Comments in opposition to clearcutting came from both timber industry and the environmental community. Most industry representatives advocated a return to selective cutting on the National Forest. They suggested management of individual trees for optimum growth rather than the broad brushed stand management approach commonly used.

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Many people within the environmental community recommended the selection system or uneven-aged management as an alternative. Maintaining biological diversity was the overwhelming justification. Concern was registered about the destruction of wildlife habitat and the conversion of our National Forest into a tree farm.

Based on these comments, a commitment was made by the Forest Management Team to analyze the feasibility of adopting a new silvicultural strategy which addressed these concerns. The proposed analysis of new management strategies required the development of managed yield tables which outlined a prescription to both maintain a characteristic uneven-aged landscape for ponderosa pine (Pinus ponderosa) and mixed conifer forest types and provide for a predictable sustained yield. Along with yield tables, new cost and value data for economic analysis needed to be generated. Descriptions of suitable stand and site condition were needed, and finally, the total number of acres on which this new strategy could be applied. With this information in place, testing could be done within the Draft Plan's preferred alternative using the Forplan model (Johnson et al., 1980). The effects of a new management strategy on the Forest's present net value (PNV), allowable sale quantity (ASQ) and long term sustained yield capacity (LTSYC) would need to be evaluated. Based on this evaluation, a decision could be made to accept or reject the notion of applying new silvicultural prescriptions on the Forest.

UNEVEN-AGED STRATEGIES DEFINED

As a first step in the development of new yield tables, three different silvicultural prescriptions were outlined which appeared to maintain the characteristic forest stand as described by the Management Team. These prescriptions were developed without strong consideration for the classic principles of uneven-aged management. Uneven-aged management per se was not seen as the real issue.

The first strategy employed a shelterwood seed cut, reserved vigorous immature saplings and poles, and regenerated a fully stocked seedling-sized stand. The shelterwood overstory was retained until the seedling-sized stand grew to a height of 15 feet. At that time, the majority of the shelterwood trees were harvested, reserving two or three large trees per acre. The understory was precommercially thinned and managed through the remainder of the rotation as an even-aged stand. Stand density was maintained at acceptable levels through a series of commercial thinnings, always cutting from below.

The second strategy was identical to the first until the point of overstory removal. In the second strategy, the shelterwood overstory was never removed and the new stand was allowed to develop beneath the canopy of shelterwood trees and the reserved saplings and poles.

The third strategy borrowed in part from past strategies used to manage ponderosa pine on public lands in the West and from current strategies used by private landowners. This prescription employed a series of three partial removal entries, each separated by a 20 year period. At each harvest entry, approximately one third of the trees greater than 16 inches and 20 percent of the trees between 9 and 16 inches were randomly removed as well as a portion of the smaller trees, representative of logging damage to the understory. The initial stand structure is maintained through this series of harvest entries, although the representation by trees greater than 16 inches was reduced dramatically over time and replaced by more vigorous trees of smaller size. Between three and six trees greater than 16 inches were retained following the final partial removal entry. Following these three entries, stand density was managed through a series of thinnings, always cutting from below. Natural regeneration was periodically introduced into the stand following harvest entries.

A fourth strategy, the standard clearcut, was also modeled. In this case, a few green trees per acre were retained for cavity dependent wildlife species and a portion of the trees less than 9 inches DBH were randomly removed, representative of logging damage to the understory. The stand was planted and later stand density was managed through a series of thinnings, always cutting from below. The clearcut strategy was introduced as a baseline against which the three uneven-aged strategies were compared.

THE PROGNOSIS MODEL

The Prognosis Model (Stage, 1973) was selected for use in developing uneven aged yield tables. A geographic variant of Prognosis, The South Central Oregon/ Northeastern California Prognosis (Johnson et al.,1986) was used for the analysis. This variant, known by the acronym SORNEC, was recently calibrated for the Forest and this exercise represented its first practical use.

Since Prognosis is an individual tree model, a wide variety of forest types can be accommodated, as can any structure ranging from even-aged to uneven-aged (Johnson et al., 1986). Tree data used for calibration, however, were generated from even-aged stands. The substantially different interrelationships between trees in uneven-aged stands were not incorporated into the calibration. Although Prognosis can accommodate an uneven-aged structure, the model's ability to predict the growth and development of uneven-aged stands over time was relatively untested.

Actual stands were modeled using Prognosis keyword files which represented each of the four strategies. Each strategy was allowed to operate for 150 years, the planning horizon used in the Forplan model. In Forplan, 150 years became the rotation age for uneven-aged management prescriptions whereas the other management prescriptions retained their original shorter rotations. The Region 6 Timber Stand Exam Program was the source of individual tree data for these stands. Forty six actual stands were selected which represented a broad range of conditions and structures across the Forest. All stands which were modeled displayed multiple canopy levels which suggested opportunities for uneven-aged management. Stands which were essentially even-aged, dwarf mistletoe infected or otherwise did not suggest opportunities for uneven-aged management were not modeled.

CALIBRATION AND TESTING

Before the Prognosis model could be used with confidence on the Forest, calibration and testing was necessary. First, a series of runs were made which tested the precalibrated height and diameter growth funtions. For these tests, seedlings were planted on site prepared ground, precommercially thinned and later commercially thinned, mimicking the existing managed yield tables. The intent was to determine if the diameter and height growth funtions used in the calibration produced trees of the predicted size at the appropriate time. Managed yield tables were used as the benchmark. Diameter and height growth adjustments were made using keywords which were later incorporated into keyword files. While these adjustments were developed from a bare ground simulation, they are appropriately used to adjust diameter and height growth in the actual stands used to produce uneven-aged yield tables.

Mortality functions were checked by allowing the 46 stands to grow without treatment for 5 decades using only the keywords which adjusted growth. Percent change in net growth per decade for these stands, segregated into the appropriate stratum and averaged, was compared with empirical stand projections developed from Forest inventory data for the same period. Based on this test, adjustments to the basic mortality functions were unnecessary.

The sensitivity of Prognosis to the interrelationship between trees of different sizes was tested next. A downward yield adjustment had been made in the existing managed yield tables to accommodate the competitive effect of retaining a few large diameter green wildlife trees above a managed stand. The adjustment had been made based on a procedure using the ecological concept of maximum biological potential. This analysis was repeated again using Prognosis and the 46 stands used to develop uneven-aged yield tables. The comparison between Prognosis and the earlier effort were remarkably close. In addition, the diameter growth of individual trees representing most size classes and competitive situations were tracked over the 150 year period. Diameter growth seemed reasonable for the stands evaluated.

STRATEGIES COMPARED

Comparisons were made between the net cubic foot volume produced by the three alternative silvicultural strategies and the standard clearcut. To develop this comparison of strategies for each stand, net cubic foot volume was accumulated from each harvest entry and added to the residual stand volume at the end of the 150 year planning period. These stand specific comparisons were summarized for the two productivity strata in ponderosa pine and three productivity stratum in mixed conifer. These same strata were used in the development of both empirical and managed yield tables used in the Forest Plan. The comparison results are displayed in Table 1. This method was chosen rather than the use of mean annual increment (MAI) since MAI was not entirely appropriate for comparison purposes due to the overlapping rotations using this uneven-aged strategy.

TABLE 1. Strata average yield comparison (net cubic foot volume per acre, sum of all harvest entries and residual volume projected for 150 year planning period) for clearcut and three alternative strategies and percent change compared to the clearcut strategy (1/ Meyer ponderosa pine site index, McArdle Douglas-fir site index for mixed conifer)

	Silvicultural Strategies			
productivity stratum 1/	standard clearcut	Strategy 1 shelterwood, age 15 remove overstory	Strategy 2 shelterwood, never remove overstory	Strategy 3 3 partial removal entries
ponderosa pine 83	12.58 2/	11.61 (-8%) 3/	9.58 (-24%)	12.32 (-2%)
ponderosa pine 78	8.59	8.18 (-5%)	6.62 (-23%)	8.59 (0%)
mixed conifer 99	15.50	15.95 (+3%)	11.95 (-23%)	14.61 (-6%)
mixed conifer 74	11.78	12.15 (+3%)	11.00 (-7%)	11.48 (-3%)
mixed conifer 68	9.36	9.04 (-3%)	8.12 (-13%)	8.53 (-9%)

2/net cubic foot volume per acre
3/net cubic foot volume per acre and percent change in yield relative to the clearcut strategy

Essentially the only difference between the standard clearcut and Strategy 1 is the influence of a shelterwood overstory of between 8 and 15 trees per acre for a 15 year period. Table 1 suggests this influence can be either positive or negative, apparently as a function of site quality and the characteristics of the individual stands modeled. Stands on better sites with vigorous and full crowned shelterwood trees actually produce more net cubic foot volume than the standard clearcut, even when shelterwood trees are retained for as long as 15 years.

The difference between Strategy 1 and Strategy 2 is more dramatic. Here the shelterwood overstory influences stand growth and development during the entire 150 year planning period. In addition, Strategy 2 maintains a greater density until stands are commercially thinned. In this case, good stocking level control is not achieved until late in the rotation. Rarely is more than one commercial thinning attainable. Strategy 1 typically achieves two and on better sites three commercial thinnings during a rotation.

Table 1 suggests that Strategy 3 compares favorable with the standard clearcut prescription in ponderosa pine. In the mixed conifer stratum, the comparison is slightly less favorable. Because of concerns about the insect and disease impacts associated with uneven-aged management in the mixed conifer forests, an additional adjustment was made outside the Prognosis model to account for volume loss associated with root and stem decays as well as western spruce budworm and Douglas-fir tussock moth outbreaks beyond those predicted for the clearcut strategy.

Individual stands within each productivity strata performed with great variability when compared with the strata average. Within the ponderosa pine stratum, yields for individual stands using Strategy 3 ranged from a 20 percent increase to a 26 percent decrease compared to the clearcutting strategy. For Strategy 3, stands with multiple canopy layers and a well stocked sapling and pole-sized stand component performed best. Even-aged old growth stands with poorly developed canopy layers and poor stocking in the saplings and pole-sized stand component performed poorly.

A PREFERRED STRATEGY EMERGES

Based on the analysis of these three alternative strategies, the Forest Management Team recommended that Strategy 3, the strategy with three partial removal entries should be developed into a set of free form managed yield tables and be incorporated into the Draft Forest Plan's preferred alternative for further testing. Yield tables were developed for each of the five strata based on the strategy outlined in the Prognosis keyword files and on the yield stream produced by the series of Prognosis runs. Yield results for individual stands within the stratum were summarized to produce an average yield. These yield tables were adjusted to depict the same initial net cubic foot volume as the existing empirical yield tables. Over the 150 year planning period, the uneven-aged yield tables for ponderosa pine were adjusted so that they produced the same total volume as the sum of the initial empirical volume harvested by clearcutting and the managed yield volume produced using the existing managed yield tables. In mixed conifer, the uneven-aged yield tables were adjusted so that they produced between 15 and 20 percent less than the clearcutting strategy to reflect the additional volume falldown associated with insect and disease problems.

PERFORMANCE IN FORPLAN

The Forplan model was first given free will to select the uneven-aged stategy from among the other available management strategies, including overstory removal and clearcutting. The uneven-aged strategy was never selected by the model. Although uneven-aged investment costs were lower than the clearcut strategy, deferring the harvest of much of the available stand volume for 20 years or more had a dramatic effect on the stand's present net value.

The Forplan model was next constrained to apply the uneven-aged prescriptions on 125,000 acres of ponderosa pine and 28,000 acres of mixed conifer across the Forest. With this constraint in place, the PNV of the Forest dropped by 4 percent, from 737 to 704 million dollars when compared to the preferred alternative in the Draft

Plan. The first decade allowable sale quantity measured in net cubic feet dropped by 4 percent from 466 to 448 million cubic feet.

The Forest Management Team felt that these changes in PNV and ASQ were reasonable. After presenting this analysis to the Regional Forester and his Staff, they concurred that these changes seemed reasonable, particularly in response to the public reaction to clearcutting.

WHAT'S IN THE FUTURE?

Based on public concerns about clearcutting and the results of the analysis, the Final EIS for the Deschutes will likely incorporate direction for uneven-aged management of ponderosa pine and mixed conifers. Management direction will place emphasis on the use of uneven-aged systems where individual stand and site conditions are appropriate. The implementation of uneven-aged management will be controlled by standards and guidelines incorporated into the Final EIS.

With these guidelines in hand, the Forest will proceed cautiously with the implementation of uneven-aged management. Initial prescriptions will be applied in ponderosa pine stands where conditions appear ideal. Prognosis will be used in the development of silvicultural prescriptions. Area specific keyword files will be developed to quickly model both clearcut and uneven-aged prescriptions. From these computer simulations, comparisons of growth and yield can be made and presented to the interdisciplinary teams responsible for timber sale environmental assessments. These tradeoffs in growth and yield can be weighed against the other positive or negative impacts associated with uneven-aged management. Prognosis can be further used to fine tune silvicultural prescriptions for timber stands where uneven-aged management is the selected alternative. Using Prognosis and an iterative process, marking guidelines can be developed to take advantage of the existing growing stock while slowly moving the stand toward a more uneven-aged structure.

Our changing management philosophy and our movement toward uneven-aged silvicultural systems comes in response to a public who places increased emphasis on the forest's recreational and aesthetic values and on a common sense, cost effective approach to forestry. Uneven-aged management of ponderosa pine is not new. Since the turn of the century foresters have looked at alternatives for managing ponderosa pine to meet the management objectives important at the time. What is new is that only now have we been able to demonstrate what we think are the growth and yield consequences of these strategies. Using Prognosis, we can show to our publics what we think the tradeoffs really are. We've been able to demonstrate that as a result of their overwhelming responses to our Draft EIS, we have the ability to make important changes in the shape of forest management on the Deschutes. Hopefully, these changes will be able to meet the needs of all.

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FOREST GROWTH MODELING IN THE SOUTHERN REGION, NATIONAL FOREST SYSTEM

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ABSTRACT. The Southern Region Growth & Yield System, SRGYS, is an attempt to combine individual tree growth models and stand level growth models currently available for the Region into one computer program. The program integrates input and output from each model into a common format. Growth models selected for inclusion in SRGYS cover the major forest types, ages, and stand conditions in the Region. Silvicultural treatments are also simulated. Applications are projection of stand growth and prediction of volumes for the Silvicultural Prescription process and for Forest planning. SRGYS is currently under development.

INTRODUCTION

The Southern Region of the National Forest System consists of a tier of states from Texas across the southern and southeastern states up to Virginia. Within this area the National Forest System manages more than 6 million acres of softwood trees and more than 4 million acres of hardwoods and mixed species. Management of this resource is a complex affair due to the multiple resource considerations. One essential component of the process is predicting stand growth and future harvest volumes.

An effort is now underway to develop a computer program which will simulate the growth and yield of stands of most forest types, stand conditions, species mixtures, and management regimes in the Southern Region. This program (SRGYS - the Southern Region Growth & Yield System) will find its main use in Forest Land Management Planning (FLMP) and in Silvicultural Prescription Analysis. When used for FLMP, SRGYS will produce the extensive yield information needed by FORPLAN, a resource allocation system. When used for Prescription analysis, SRGYS will allow examination of stand exam data for simulation of alternative harvest schemes.

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In order to produce growth and yield values for the varied conditions in the Region, SRGYS combines growth models developed from many sources into one framework. This framework consists of these main components:

Stand Description	(Age, Site Index, Density)
Stand Growth	(From various research papers)
Stand Treatments	(Cutting)
Economics	(Based on local values)

STAND DESCRIPTION

At the current time SRGYS consists of eight growth models from various research papers. Each growth model (selected according to Forest Type) requires a description of the existing characteristics of the stand to form the basis for a prediction of future growth. All growth models require Age, Site Index, and a measure of Stand Density. Density is specified as basal area/acre (in sq.ft.) or number of trees/acre for the stand depending on which growth model is selected.

The stand density is converted to a diameter distribution of number of trees/acre by one inch diameter class. SRGYS carries this diameter distribution through the growth cycles to facilitate computations of volumes by products. The option for using individual tree growth projection allows entry of a diameter distribution as measured data or as generated by distribution functions within SRGYS.

When the initial stand description is complete, a display of the stand is shown. This display presents stand level values and diameter class values as seen in Figure 1.

STAND GROWTH

Growth and yield models developed by researchers from the Forest Service Experiment Stations and from Universities have been converted to computerized form and included as the growth models in SRGYS. Growth is computed on a stand basis or on an individual tree basis according to the model chosen. In each case a diameter distribution is carried along through time.

The choice of growth model can be made directly by people who are familiar with the models' characteristics. Otherwise, SRGYS can select the growth model based on forest type, geographical location, thinning or o thinning, and plantation or natural origin.

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STAND SUMMARY --   After Projection                         Period=  1 of  1
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
Stand Name : COMP-1,STAND-317                Year= 1990.        Age      = 30.0
Forest Type: 31 Loblolly Pine                Site=   60.        Base Age= 25.0
Total Trees/ac=  504.5        Height Dom&Codom= 66.2   Quad.Mean Diam=  8.2
Basal Area (LIVE) TOTAL=186.2  SAW=101.0  SRW = 84.9  SAP=    .3 SQ.FT/AC
Basal Area (CUT)  TOTAL=    .0  SAW=    .0  SRW =   .0  SAP=    .0 SQ.FT/AC
Average tree AGE=  30.0  Southern Pine Beetle Hazard Rating=   HIGH risk.
Live Stand Value= $ 1510.87 per Acre.     Cut Stand Value= $      .00 per Acre.


                    ---- Species= 131  Loblolly Pine ----      $1510.87/ACRE
 ---------------------- LIVE ----------   ---------- CUT --------  ---DEAD----
 DBH  TREES     BA   HT  CR   CUFT   BDFT   TREES  BA   CUFT   BDFT  TREES   BA
  4     2.9     .3  44.   .      .      .      .    .      .      .     .     .
  5    16.7    2.3  51.   .    63.      .      .    .      .      .     .     .
  6    49.7    9.8  55.   .   286.      .      .    .      .      .     .     .
  7    98.1   26.2  59.   .   801.      .      .    .      .      .     .     .
  8   133.7   46.7  62.   .  1477.      .      .    .      .      .     .     .
  9   119.8   52.9  64.   .  1663.  4931.      .    .      .      .     .     .
 10    63.8   34.8  66.   .  1106.  3935.      .    .      .      .     .     .
 11    17.6   11.6  68.   .   373.  1509.      .    .      .      .     .     .
 12     2.1    1.7  69.   .    54.   241.      .    .      .      .     .     .
---  ------  ---- ---- ---  -----  ----- ----- -----  -----  ----- ----- -----
ALL   504.5 186.2  61.  .0  5823. 10616.     .0   .0     0.     0.    .0    .0
==============================================================================

Stand Growth set by MODEL=  8.     Diameter Distribution set by MODEL=  8
Volume Source: McClure & Cost.  SEFES     Board Foot Rule: INT. 1/4
Short Roundwood DBH limit: Softwood= 5.0 to  9.0,   Hardwood=  5.0 to  11.0
Sawtimber       DBH limit: Softwood= 9.0 and up,    Hardwood= 11.0 and up.
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Figure 1. Example of a Stand Summary display from SRGYS. The top section shows stand level information, the middle section shows the breakdown by diameter class, and the last section indicates the growth model used for the projection, the volume equation source and volume merchantability limits.

Growth models currently included in SRGYS are:

Forest Type	Characteristics	Author
Loblolly	Planted nothin	Smalley & Bailey (1974)
Slash pine	Planted nothin	Dell, et al. (1979)
Slash pine	Planted nothin	Bailey, et al. (1982)
Longleaf	Planted nothin	Lohrey & Bailey (1977)
Longleaf	Natural thin	Farrar (1950)
Sand pine	Planted nothin	Outcalt (1986)
Cove Hwd.	Natural thin	Beck & Della-Bianca (1970)
All	All - Individual tree models	STEMS, Harrison (1986)

STAND LEVEL MODELS

Most models developed for forest types in the Southern Region are stand level models that project growth of a stand level characteristic (usually basal area or trees/acre). After stand growth is estimated, diameter distribution functions are applied to produce a distribution of trees/acre (and other characteristics) by one inch diameter classes. For models that do not provide diameter distribution functions, the most appropriate functions from other research papers are used.

INDIVIDUAL TREE LEVEL MODELS

SRGYS can also predict stand growth on a tree-by-tree basis. Equations from Harrison, et al. (1986) and from STEMS (Belcher, et al. 1982) are applied according to tree species. Species for which no equations have yet been developed are projected with equations for species with similar growth characteristics. Work is in progress on developing individual tree growth projection equations for more species in the South.

STAND TREATMENTS

SRGYS simulates cutting as either a harvest cut (all trees on the stand are cut) or as a thinning (some trees are cut). Thinning can be simulated as: thin from above or below, row thin, or take all of one species. For each of these categories, cutting limits can be set as residual basal area/acre, residual number of trees/acre, percent of the stand to cut, or a limiting diameter. By applying these conditions to the cut, many types of silvicultural operations can be simulated.

These cutting options are coded in SRGYS as a multi-pass operation. This allows scenarios such as: 1) remove all water oak, 2) thin remaining trees from above to a limiting diameter of 22 inches, and 3) cut any remaining trees back to a residual basal area of 60 square feet per acre. At each step, SRGYS can display the stand summary or show the stand's current stocking level position on a stocking level chart. This information can be used in deciding how much to cut with each operation.

If it is determined that the thinning specifications have cut too much of the stand, there is an UNCUT option that allows replacement of the cut trees.

ECONOMICS

This section of SRGYS calculates the sum of the discounted costs and incomes in terms of dollars per acre. Required information is: interest rate, fixed costs, stumpage prices, and the reference year for computations. Stumpage price is specified in terms of dollars per hundred cubic feet for small roundwood and dollars per thousand board feet for sawtimber. The value of the stand is determined by applying these prices to the volumes computed by diameter class and species.

Income is automatically computed by applying the stumpage price to any trees cut in the stand treatment section. Costs are entered from the keyboard and may be designated as occurring at any year.

FUTURE PLANS

SRGYS is still under development. It has only eight growth models in it now and needs many more to completely cover the Region's range of stand conditions. SRGYS will have the capability for handling mixed species and mixed age classes but due to the scarcity of individual tree growth equations, this option does not perform well at this time. Equations presented by Harrison, et al. (1986) allow projection for some hardwood species but for softwoods, the only equations available are from the STEMS program. Thus individual tree growth of loblolly pine in SRGYS currently looks just like red pine in Minnesota. Work is in progress by Dr. Ralph Meldahl and other southern researchers to develop individual tree growth equations and these equations will be incorporated into SRGYS as they become available.

An important part for the near future is the behavior of growth equations when applied beyond the range of the sample data from which they were developed. Current research generally does not extend to the ages necessary for National Forest planning.

The Economics section will be expanded to provide more attributes that will be useful to the Region's Silviculturists and Planners.

The topics of fertilization and genetic improvement have not yet been addressed in SRGYS. They are necessary for producing realistic stand growth projections.

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A DESCRIPTION OF THE TWIGS AND STEMS INDIVIDUAL-TREE-BASED GROWTH SIMULATION MODELS AND THEIR APPLICATIONS

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ABSTRACT. Over a decade of research has gone into the development and implementation of the models and software that comprise the STEMS and TWIGS tree and stand growth simulation systems. STEMS and TWIGS are currently calibrated for the Lake States and Central States regions, but research is in progress elsewhere to develop similar models for the northeastern and the southeastern United States. A major strength of the growth and yield models that drive these simulators is their large, regional calibration database and their ability to accommodate mixed-species, uneven-aged forest stands. A variety of adjustment and aggregation procedures have been used to improve precision and efficiency of the models for specific applications. Applications include statewide inventory projections, economic analysis of management alternatives for individual stands, inventory design, linkage to wildlife habitat models, and educational use. The implementation software operates on mainframe, mini, and microcomputers, offering processing options that range from batch processing thousands of inventory plots at once to interactively simulating results of several management alternatives for a single stand. Research to improve prediction precision is ongoing; recently, special emphasis has been placed on adjusting the regional models to account for variation due to climate.

STEMS, TWIGS, and GROW are three computer programs for simulating growth and yield. STEMS (Stand and Tree Evaluation and Modeling System) is a growth and yield program developed for batch processing (a series of stands processed without direct user interaction) inventory data on mainframe computers. It was initially designed to update and project large forest inventories such as the statewide inventories conducted by the Forest Inventory and Analysis units of the USDA Forest Service. Advances in the capabilities and availability of microcomputers have made it possible to develop software called TWIGS (The Woodsman's Ideal Growth projection System). TWIGS contains the same prediction equations as STEMS but its primary use is forecasting management alternatives for individual forest stands. TWIGS allows the user to simulate a variety of management alternatives and to evaluate the outcome of each management regime in terms of volume yield and economic return. The simplest implementation of the prediction equations, called GROW, contains only the growth and mortality models and coefficients used in STEMS and TWIGS. GROW can be integrated as a subroutine into other more complex simulation systems, enabling users to link the tree growth models of STEMS with other data sources or other models.

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THE PROJECTION PROGRAMS

The individual-tree, distance-independent models in STEMS (Belcher et al. 1982), TWIGS (Miner et al. in press, Belcher 1982), and GROW (Brand 1981a) can predict change for even- and uneven-aged stands of pure or mixed species in the North Central United States. Special features and constraints are included in the model forms to produce biologically reasonable behavior for certain rarely encountered extremes such as very dense stands and large tree diameters. Because all three projection systems implement the same prediction equations, they produce identical projections of forest change. Two geographical variants exist, one for the Lake States (Minnesota, Wisconsin, and Michigan) and one for the Central States (Indiana, Illinois, and Missouri).

The software for each projection system is written in FORTRAN (an earlier version of TWIGS is available in Pascal for Apple II microcomputers). STEMS can, in one run, sequentially project growth and yield for many forest plots or stands. STEMS also has an interactive mode that, through the use of menus, allows users to simulate change for one stand at a time. Like the interactive mode in STEMS, TWIGS projects one stand at a time. Menus guide users through the process of setting up the projection run, implementing management alternatives, and evaluating the economic return. GROW users must write their own input, output, management, and calling routines.

Table 1. A comparison of major features of STEMS, TWIGS, and GROW.

Feature	STEMS	TWIGS	GROW
Hardware	Mainframe or mini computer	PC running MS/DOS 400K RAM	Any with FORTRAN compiler
Processing	Batch or interactive	Interactive	User written interface
Input	From external file or interactive	From external file made with companion program	User written
Output	Stand level summary Updated tree list	Stand level summary Updated tree list Summary of run	User written
Management	By menu or by management diagram	By menu (includes graphical stocking guide)	User supplied
Economic analysis	Not available	By menu	User supplied
Ingrowth	Can be input by user	Can be input by user	User supplied
Regeneration	Following clearcut or shelterwood harvest	Not available	User supplied

STEMS, TWIGS, and GROW have major differences (Table 1). In general STEMS is best for processing large numbers of plots while TWIGS is the easiest to use and offers the greatest flexibility in simulating and evaluating alternative management scenarios on a plot-by-plot basis. Only TWIGS includes options for economic analysis of alternative management strategies. GROW is the easiest format from which to modify the FORTRAN code or to develop user-written applications. GROW is most often used where the growth and mortality predictions are either a part of the solution of a larger problem or where a simpler framework than STEMS or TWIGS is desirable.

INTERNAL OPERATION OF THE MODELS

Each of the software packages requires the same information about the stand to be projected. Input is in the form of a tree list that comes from a single inventory plot or from a combination of several plots representing one stand. Required plot level information includes forest name, stand name or plot number, stand age, year measured, site index, and the species of the site index tree(s). Information required for each sampled tree includes species, diameter, status (live, dead, or cut), tree class (acceptable form, undesirable form, or cull), and trees per acre represented by this tree. All models operate on a per acre basis, and the trees per acre expansion factor is used to adjust each tree list entry to its per acre representation before processing. Providing observed tree crown ratio data (percent of tree height in live crown) will increase prediction accuracy, but the program will estimate crown ratios that are missing.

As the tree list is projected, estimated annual diameter growth is added to each tree for each year in the simulation, and expansion factors (trees per acre) are decremented to account for mortality. Crown ratios, used in growth estimation, are updated to reflect current stand conditions. The STEMS/TWIGS equations were calibrated from extensive regional data bases: about 1,500 remeasured plots for the Lake States variant and about 2,500 plots for the Central States variant.

Within each variant (i.e. Lake States or Central States), four main mathematical functions calibrated with species-specific, regression coefficients drive STEMS/TWIGS predictions. Specific model forms are slightly different for the Lake States and the Central States. The first function estimates the potential diameter growth for a tree, i.e., the expected annual diameter growth of a tree growing without competition (Hahn and Leary 1979, Shifley in press). It is estimated using fast-growing dominant and codominant trees. Potential diameter growth is multiplied by a modifier function to estimate actual growth (Holdaway 1984, Shifley in press). The modifier function, constrained to produce values between zero and one, reduces potential diameter growth based on the competition affecting the tree. Because the crown ratio is used in the potential function, a third function estimates a tree's crown ratio for each year of the projection (Holdaway 1986). This same function is used to estimate missing crown ratios in the initial tree list. The final function estimates the annual probability of survival with a form of the logistic equation (Buchman _et_ _al_. 1983). Predicted mortality changes with tree size, and it decreases as vigor decreases.

MODEL EVALUATION

Even when models and software are well designed, their predictions must be evaluated. Evaluations of the Central States models (Miner et al. in press) and Lake States models (Holdaway and Brand 1986) show that, on the average, the models produce small errors (Table 2). These errors have been standardized to 10 years to compensate for the variable measurement intervals of the evaluation plots. Although the mean errors are small, the variability of the prediction errors, as shown by their standard deviation, is large. The evaluation data for the Central States model consist of a portion of the calibration data set aside before the model was developed; an independent set of data was used in evaluating the Lake States model.

Table 2. Differences between predicted and observed values after 10 years for Central States and Lake States models.

Type of Error	Mean	Standard Deviation	Number of Observations[1]
Central States			
DBH growth (in)	.07	0.7	7,241
Basal area (sq ft per ac)	0.2	14	577
Number of trees (per ac)	-7	241	577
Lake States			
DBH growth (in)	-.06	0.6	12,696
Basal area (sq ft per ac)	0.9	12	822
Number of trees (per ac)	6	65	822
Volume (cu ft per ac)	-3.6	210	822

[1] For DBH growth, the number of observations is the number of trees; for all other comparisons, it is the number of remeasured plots.

SIMULATING MANAGEMENT

As stated previously, STEMS and TWIGS offer two very different strategies for simulating management activities. All simulated harvesting in TWIGS is performed interactively from a management menu with the following cutting options:

- Remove individual trees
- Remove all hardwoods/softwoods
- Remove all trees of one species
- Remove all trees of one size class
- Remove all trees of one quality class
- Clearcut
- Thin from above/below
- Thin by dbh class
- Row thin
- Uncut

By selecting one or more of these options, it is possible to simulate most cutting strategies. Other options include viewing the tree list entries and viewing where the stand is located on graphical stocking guides.

Except for the stocking guide display, STEMS, when run in interactive mode, offers the same options as TWIGS. When STEMS is run in batch mode with the management option selected, stands are automatically managed according to a set of management diagrams developed by Brand (1981b) and Walters (in press) (Figure 1). These diagrams, derived from regional management guides and consultation with experts, are a set of rules that use information about the current stand condition to prescribe and implement a management action. Actions include thinning, clearcutting, shelterwood cutting, or doing nothing. Following a clearcut or shelterwood harvest, the STEMS regeneration algorithm will create a new stand. Users can alter the management diagrams or the regeneration algorithm to fit specific local conditions.

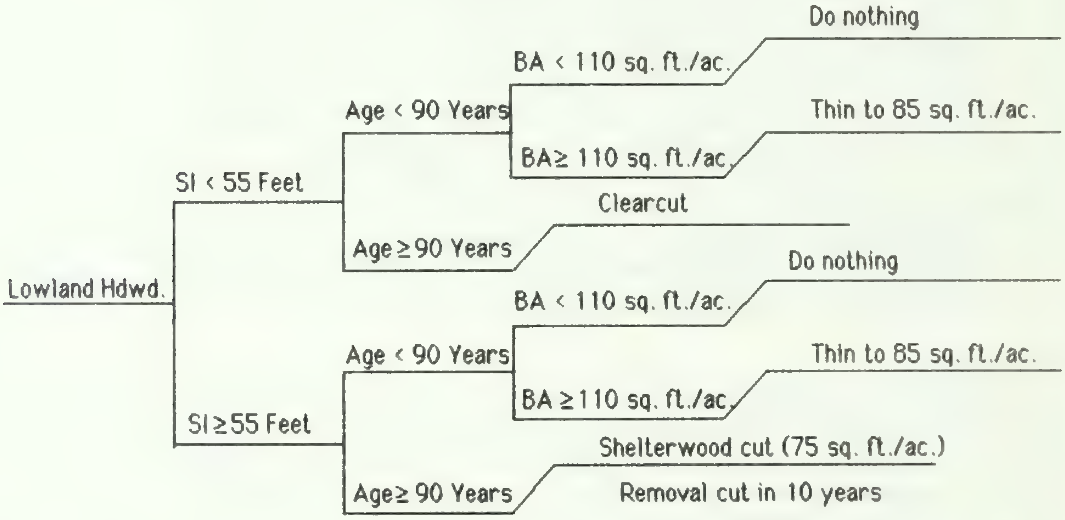

Figure 1. An example management diagram for the lowland hardwood type from Lake States STEMS. Users have the option to alter the values of site index, age, and basal area at each decision point.

ADJUSTMENTS AND EXTENSIONS

STEMS/TWIGS are regional models. Therefore, at a particular location, predicted change may differ from observed change due to a variety of factors unaccounted for in the models: factors such as variation in climate, topography, genetics, insects, disease, or anthropogenic disturbance. Several adjustment procedures have been proposed for localizing the models used in STEMS, TWIGS and GROW (Gertner 1984, Holdaway 1985, Smith 1983). A procedure to adjust models for climatic variations is currently being investigated. These procedures have been used to improve precision of the simulation for specific applications.

To reduce costs associated with projecting large forest inventories, it is sometimes desirable to combine plots with similar initial conditions and treat them as a single stand. Moeur and Ek (1981) and Ek et al. (1985), have evaluated several aggregation techniques, demonstrating that careful aggregation can lower costs with little change in per acre estimates, although some tree-level detail is sacrificed.

The mathematical models and techniques used in STEMS and TWIGS are quite general and, with little modification, can be used with different species in other regions. Currently Don Hilt, Northeastern Forest Experiment Station, and Ralph Meldahl, Auburn University, are exploring methods to apply the same techniques in the northeastern and southeastern United States.

APPLICATIONS

STEMS, TWIGS, and GROW have been used extensively and for a variety of purposes. Generally each software package is best suited for specific kinds of applications. Examples for each software package demonstrate the kind of applications possible.

STEMS

Because STEMS contains management diagrams, it is easy to project an inventory to determine treatment opportunities. Smith and Jakes (1981) estimated how many acres would be eligible for final harvest, timber stand improvement, and stand conversion during the decade following the most recent Minnesota inventory. The Forest Service and forest industry have used STEMS and its management guides extensively in predicting the yields expected for stands treated in different ways. Estimated yields were linked to cost and revenue data in linear programming models to determine the mix of timber investments that maximize net returns. A necessary part of these applications is the capability of the STEMS management guides to be easily changed to reflect an organization's range of current or anticipated management regimes.

TWIGS

TWIGS' interactive management and economics analysis make it ideal for evaluating the financial impact of management alternatives. Red pine (Pinus resinosa) plantations managed for pulpwood and saw logs were compared with plantations managed only for pulpwood (de Naurois and Buongiorno 1986). Shifley et al. (1986) used a modified version of TWIGS to evaluate the effect on timber yield, financial return, and habitat quality for gray squirrel. They incorporated a habitat suitability index model for gray squirrel into TWIGS and compared a treatment based solely on silvicultural considerations with a treatment that also considered aesthetics and wildlife needs.

GROW

GROW has been used by a forest products company to annually update its forest inventory. Inventory plots are remeasured periodically and also after cutting occurs in the stand. Those plots not remeasured during the current year are projected to produce an updated inventory. GROW has also been modified and included in a dynamic programming package used to determine optimal thinning strategies (Stone and Ek 1985).

CONCLUSION

Because of their ability to predict change in any stand encountered in the North Central region, STEMS, TWIGS, and GROW can help forest managers evaluate alternatives and prepare plans for these diverse forests. Depending on the desired application, one of the three programs will provide a better framework than the others for predicting this change. As improvements are made to the models and other components added, it will be possible to improve accuracy for long projections and specific locations.

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SOFTWARE

Program Name: TWIGS 3.0 (Lake States or Central States variant)

Programmers: Kevin Nimerfro, David Belcher, David Kowalski, Monique Belli

Hardware and Software Requirements:

Computer model ---------------------------- IBM PC or compatible
Operating system -------------------------- DOS 2.1 or higher
Memory required --------------------------- 384K
Disk drives required ---------------------- 1 floppy (2 floppies or hard drive preferable)
Printer required -------------------------- no

Additional Information:

Developed at: North Central Forest Experiment Station
1992 Folwell Avenue
St. Paul, Minnesota 55108

Program Available From: Forest Resources Systems Institute
Courtview Towers, Suite 24
210 N. Pine Street
Florence, Alabama 35630
(205) 767-0250
or
North Central Forest Experiment Station
1992 Folwell Avenue
St. Paul, Minnesota 55108
(612) 649-5173

Media: Floppy disk and user's manual

Cost: Write for current prices

Program Name: STEMS (Lake States or Central States variant)

Programmers: Kevin Low and David Belcher

Hardware and Software Requirements:

Computer model ---------------------------- Mainframe or mini
Operating system -------------------------- Any plus FORTRAN compiler
(1977 standard)
Memory required ----------------------------

Additional Information:

Developed at: North Central Forest Experiment Station
1992 Folwell Avenue
St. Paul, Minnesota 55108

Program Available From: North Central Forest Experiment Station
1992 Folwell Avenue
St. Paul, Minnesota 55108
(612) 649-5173
(write or call for order form)

Media: Magnetic tape

Cost: $25.00

Program Name: GROW (Lake States or Central States variant)

Programmers: Kevin Low and Gary Brand

Hardware and Software Requirements:

Computer model	Mainframe, mini computer, or microcomputer
Operating system	Any plus FORTRAN compiler (1977 standard)

Additional Information:

Developed at: North Central Forest Experiment Station
1992 Folwell Avenue
St. Paul, Minnesota 55108

Programming skills required to incorporate into other application program.

Program Available From: North Central Forest Experiment Station
1992 Folwell Avenue
St. Paul, Minnesota 55108
(612) 649-5173

Media: 5 1/4" MS-DOS compatible floppy disk

Cost: 5 1/4" floppy disk with request

AN INTRODUCTION TO "COMPREHENSIVE OUTLOOK FOR MANAGED PINES USING SIMULATED TREATMENT EXPERIMENTS-PLANTED LOBLOLLY PINE" (COMPUTE_P-LOB)

R. B. Ferguson and V. C. Baldwin, Jr.[1]

ABSTRACT. "Comprehensive outlook for managed pines using simulated treatment experiments-planted loblolly pine" (COMPUTE_P-LOB) is a computer program used to predict growth and yield for both thinned or unthinned loblolly pine stands. Entry options allow the user to examine the future effect of thinning or not thinning a stand. The initial variables required to run the system are age, a measure of stand density, and a measure of site quality. Predicted stand/stock tables are generated by the program for unthinned, before-thinned, and after-thinned stands. The tables reflect either volume, green-weight, or dry-weight predictions. Tables of the stand components removed by thinning can also be produced to aid in merchandizing the stand.

INTRODUCTION

COMPUTE_P-LOB is an interactive computer program for predicting the future growth and yield of thinned and unthinned loblolly pine plantations. This paper serves as an introduction to the software (Ferguson and Baldwin, 1987) used to operate the growth and yield prediction system developed by Baldwin and Feduccia (1987). The prediction system will predict either volume (cubic- and board-foot) or weight-per-acre yields (green- or oven-dry pounds). A wide selection of options is available for processing and generating stand predictions. The user may test the effects of varying stand attributes and treatments to generate extensive stand and yield table information. The current data set limits predictions to plantations from 10 to 50 years old.

COMPUTE_P-LOB has some things in common with the USLYCOWG model (Feduccia et al., 1979) which predicted growth and yield for unthinned stands through age 30 only. Both use a similar input format, were developed from the same data for the unthinned condition through age 30, and use the same initial survival equation. However, COMPUTE_P-LOB models the unthinned stand beyond age 30 as well as thinned stands through age 45 and was constructed using the whole stand projection--parameter recovery--diameter distribution approach of Matney and Sullivan (1982). This method allows the user to estimate the diameter distribution parameters from equations that predict measurable stand parameters rather than by estimating the parameters directly.

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PROGRAM OPERATION

The COMPUTE_P-LOB program is currently available in FORTRAN-77 for the IBM-PC/XT with the Microsoft DOS 2.10, the Data General MV/X000 series, and Digital Equipment Corporation's PDP/11 and VAX series computers. BASIC versions are currently available for the IBM-PC and are being developed for the Apple Computer Company's Apple IIc Microcomputer.[1]

COMPUTE_P-LOB assumes one of three general situations: (1) starting and ending with an unthinned stand; (2) starting with an unthinned stand, thinning at some age, and ending with a stand thinned a variable number of times; or (3) starting with a previously thinned stand and ending with a stand thinned a variable number of times. These situations, the required initial values, and the prediction process are summarized schematically in Figure 1. The abbreviations used in the program are: A (stand age), HD (height of the dominant and codominant stand component), SI (site index), TS (trees surviving per acre), BA (basal area per acre), DBH (diameter at breast height), DMIN (minimum diameter), QMD (quadratic mean diameter), P93 (diameter of the 93rd percentile), and TP (trees planted per acre).

The required initial inputs for the program are: the stand age, either the mean height of the dominant and co-dominant trees or the site index, and either current trees surviving, basal area, or trees planted per acre. The inclusion of certain additional optional information will make it possible for other equations available within the system to be used, which, while requiring more initial information, are mathematically more reliable in their predictions.

Normal program operation involves responding to a set of questions keyed to the user's particular situation. The user should note that some questions require multiple responses. As an example, let us use a 15-year-old stand, a site index of 60 feet (base age 25), and 500 trees surviving per acre. We want to know the stand volume for merchantablity limits of 0- ,4- ,and 8-inch top diameters. The following reproduces the program display as seen by the user. The brackets [ ] are used to indicate the user's responses--they are not to be used as part of the response--and are included as part of the example.

SCREEN DISPLAY

```
     Choose your output device
         S = Screen output
         H = Hardcopy printer
 [S]
     Enter a label for your output (60 characters or less)
 [EXAMPLE OUTPUT]
```

---

[1] The use of trade, firm, or corporation names in this paper is for the information and convenience of the reader. Such use does not constitute official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

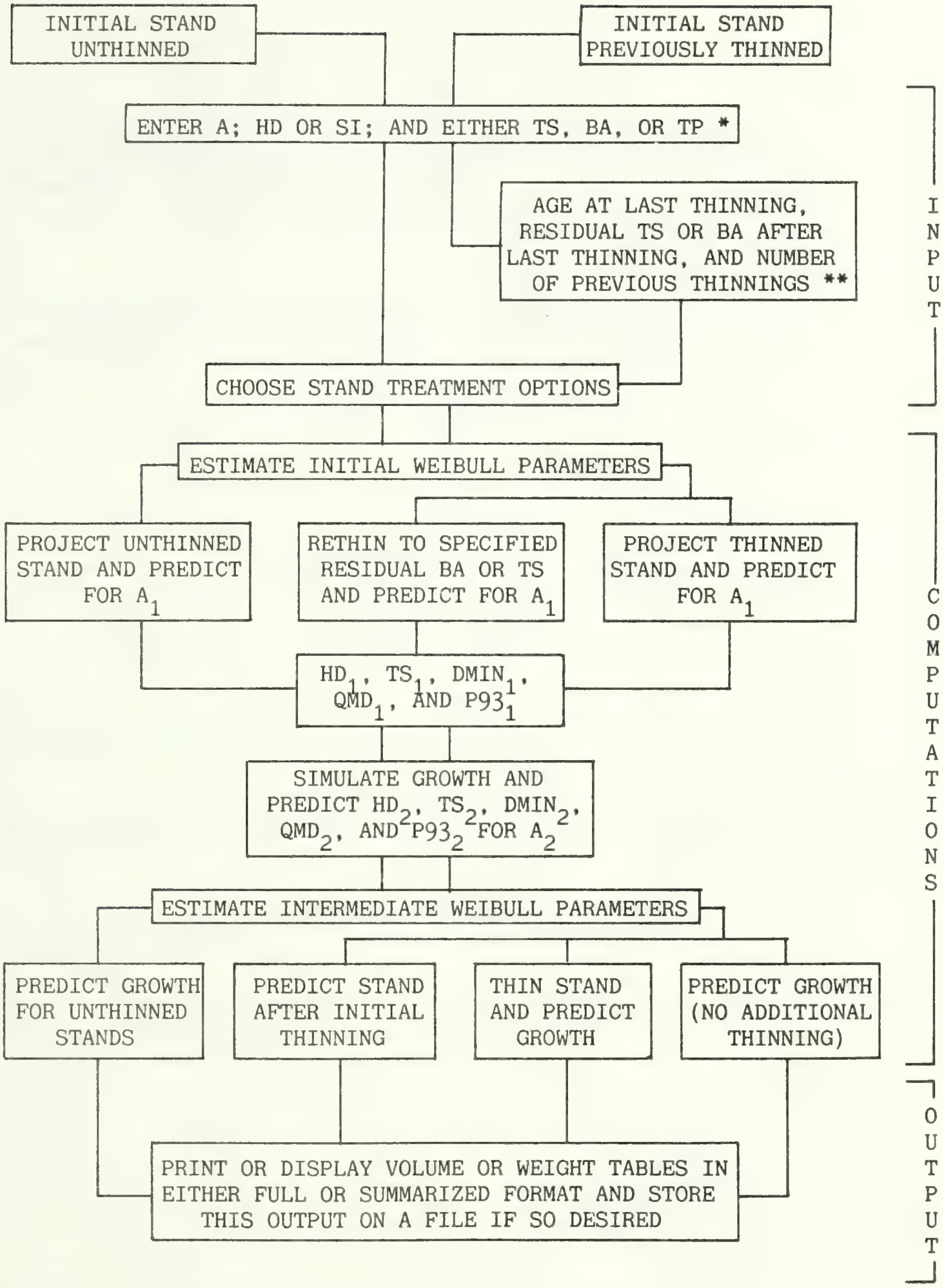
INITIAL STAND UNTHINNED
INITIAL STAND PREVIOUSLY THINNED
ENTER A; HD OR SI; AND EITHER TS, BA, OR TP *
AGE AT LAST THINNING, RESIDUAL TS OR BA AFTER LAST THINNING, AND NUMBER OF PREVIOUS THINNINGS **
CHOOSE STAND TREATMENT OPTIONS
INPUT
ESTIMATE INITIAL WEIBULL PARAMETERS
PROJECT UNTHINNED STAND AND PREDICT FOR A_1
RETHIN TO SPECIFIED RESIDUAL BA OR TS AND PREDICT FOR A_1
PROJECT THINNED STAND AND PREDICT FOR A_1
HD_1, TS_1, $DMIN_1$, QMD_1, AND $P93_1$
SIMULATE GROWTH AND PREDICT HD_2, TS_2, $DMIN_2$, QMD_2, AND $P93_2$ FOR A_2
ESTIMATE INTERMEDIATE WEIBULL PARAMETERS
PREDICT GROWTH FOR UNTHINNED STANDS
PREDICT STAND AFTER INITIAL THINNING
THIN STAND AND PREDICT GROWTH
PREDICT GROWTH (NO ADDITIONAL THINNING)
COMPUTATIONS
PRINT OR DISPLAY VOLUME OR WEIGHT TABLES IN EITHER FULL OR SUMMARIZED FORMAT AND STORE THIS OUTPUT ON A FILE IF SO DESIRED
OUTPUT

Figure 1. Generalized schematic representation of the loblolly pine growth and yield prediction system COMPUTE_P-LOB (* These initial inputs are required for all stands, ** these inputs are required only when starting with a previously thinned stand). Meanings of abbreviations are also given in the text.

```
     Describe the stand by answering the following questions.  Enter a
     zero (0) if you do not know the answer to a question requiring a
     numeric response.  Use the designated character responses where
     indicated.  Certain questions have a preset default response
     (Indicated by an asterisk (*) following the default).  If you accept
     the default, press the RETURN key.

     At the very least you must provide STAND AGE, a measure of DOM/CODOM
     HEIGHT, and a measure of STAND DENSITY.  If you are starting with the
     closing values of a previous run of the model, the answers must come
     from that output in order to set up the new run.

     Are you starting with the closing values for a previous run of this
     program?
         Y = Yes
         N = No (*)
[N]
     Stand age?
[15]
     Height of dominants and codominants?
[0]
     Site index?
[60]
     Site index base age?
[25]
     Surviving trees per acre?
[500]
     Has this stand been thinned before?
         Y = Yes
         N = No (*)
[N]
     Are your initial stand inputs entered correctly?
         Y = Yes (*)
         N = No
[Y]
     How many new thinnings? -- (Must be LE 10)
[0]

     Choose form of output:
         V = Volume (*)
         G = Green weight
         D = Dry weight
[V]
     Enter three top diameter limits for volume tables
     (0=total volume).
         (Example: 0,4,8 for total volume, volume to a 4-inch top,
                   and volume to an 8-inch top, respectively.)
[0,4,8]
     Do you want single table per page or continuous output:
         S = Single table per page
         C = Continuous feed (*)
[C]
```

```
      Choose form of output tables:
          F = Full tables (*)
          S = Summary tables
 [F]
      Choose a board-foot volume rule:
          I = International 1/4 (*)
          S = Scribner
          D = Doyle
 [I]
      Number of stand tables (Do not include any cut tables
      in your count)?  NOTE: You must run the before-thin
      situation at a given age before you can run the after thin.
 [1]
      For each stand table requested enter the age and
      the thinning code:
          N = No thinning
          B = Before thinning
          A = After thinning
                   (Example of input: 10,N; for age 10,
                   no-thin table)
      For stand table# 1, enter age and thinning code.
 [15,N]
      Are your stand table specifications correct?
          Y = Yes (*)
          N = No
 [Y]
      Please wait.  Your request is being processed.
```

(After all tables have been output the user will be asked about storing the output on a disk file. If you want to store this information you must specify a proper file name and storage device as required by your system.)

```
      Do you want to save your output on a disk file?
          Y = Yes
          N = No (*)
 [N]
      Do you want to continue?
          Y = Yes (*)
          N = No
 [N]
```

(This response will cause the program to terminate.)

The program can produce up to fifteen (15) stand/stock tables per run in either a detailed or summarized format for volume, dry weight, or green weight. The user also has the option of printing cut tables when thinning as a quick reference of what the model removed from the stand by thinning. The cut tables do not count against the number of stand tables. The results of the above example are presented in Figure 2.

```
      EXAMPLE OUTPUT

                               LOBLOLLY PINE
                            NO THINNING THIS YEAR
                                   (PER ACRE)

     AGE=   15
     DOMINANT HEIGHT= 44.5 FEET
     QUADRATIC MEAN DBH=  6.337 INCHES
==============================================================================
                                 CUBIC FOOT VOLUME OF STEMS           INTER.1/
 DBH  STEMS BASAL AV.            TO AN O.B. TOP DIAMETER OF           B.F. VOL
CLASS       AREA  HT.     0 INCHES        4 INCHES        8 INCHES    8-IN. TO
             sq.        ------------    ------------    ------------
 in.   no.   ft.  ft.   o.b.    i.b.    o.b.    i.b.    o.b.    i.b.     i.b.
------------------------------------------------------------------------------
   2     1   0.0  19      0.      0.      0.      0.      0.      0.       0.
   3    16   0.8  28     12.      8.      0.      0.      0.      0.       0.
   4    54   4.7  35     88.     63.      0.      0.      0.      0.       0.
   5   101  13.8  39    281.    204.    184.    129.      0.      0.       0.
   6   129  25.3  42    546.    403.    456.    332.      0.      0.       0.
   7   110  29.4  44    653.    488.    599.    444.      0.      0.       0.
   8    62  21.6  46    496.    374.    474.    355.      0.      0.       0.
   9    22   9.7  47    225.    170.    219.    165.     97.     69.       0.
  10     5   2.7  48     64.     48.     63.     48.     38.     28.     151.
------------------------------------------------------------------------------
       500 108.1       2365.   1758.   1995.   1473.    135.     97.     151.
==============================================================================
  SI(BASE AGE  25)=  60 FEET;  93RD PERCENTILE=  8.353
  WEIBULL PARAMETERS:  "A"=  1.703;  "B"=  4.969;  "C"=  3.359
```

Figure 2. Example of program output for the volume option.

PROGRAM AVAILABILITY

The computer program described in this paper is available on request with the understanding that the U.S. Department of Agriculture cannot assure its accuracy, completeness, reliability, or suitability for any other purpose than that reported. The recipient may not assert any proprietary rights thereto nor represent it to anyone as other than a Government-produced computer program. For cost information, please write to either of the authors at the Southern Forest Experiment Station, 2500 Shreveport Highway, Pineville, LA 71360.

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STAND: AN INTERACTIVE MODEL TO SIMULATE THE GROWTH AND YIELD OF WOODLANDS IN THE SOUTHWEST

Peter F. Ffolliott, William O. Rasmussen, and D. Phillip Guertin[1]

ABSTRACT. An interactive computer simulation model, called STAND, has been developed to predict the impacts of land management practices on the growth and yield of pinyon-juniper and oak woodlands of the Southwest. Depending upon the structure of the simulation exercise, growth and yield estimates can be generated for initial conditions, at some point in the future under the initial land management practices, or after the implementation of alternative land management practices. In many respects, the simulation options in STAND involve applications of a simplified version of TRAS (Timber Resource Analysis System), a widely used computer program for the projection of forest resources in the United States (Larson and Goforth 1970, Alig et al. 1982)

INTRODUCTION

Although the growth and yield of individual stands are the focus of STAND, these stands can be aggregated to represent larger woodland communities, if desired. With increasing emphasis being placed on the management of the woodlands in the Southwest, outputs from STAND can improve the basis for selecting the best course of management.

Woodlands under consideration in this paper are the extensively found pinyon-juniper woodlands and the more limited oak woodlands. Traditionally, both woodland types have been managed and utilized for multi-benefits, although the production of wood has been "secondary" to other uses in many instances. In recent years, the managememt of both the pinyon-juniper and oak woodlands for primary wood production has increased in emphasis, largely due to the potentials for fuelwood utilization. It follows, therefore, that estimates of the growth and yield of woodlands in the Southwest are important to appropriate decisionmaking for sustainable fuelwood production.

FORMULATION OF MODEL

STAND determines the gross change in number of trees per hectare in 5-centimeter dbh classes for a projection period, assuming that the change in a future period will equal that of a past period. This relation is given by:

$$T = G_I - G_O \qquad (1)$$

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where T is change in number of trees in a 5-centimeter dbh class, G_I is growth into the 5-centimeter dbh class, and G_O is growth out of the 5-centimeter dbh class.

The change in number of trees per hectare for each 5-centimeter dbh class is multiplied by the average individual tree volume for that class and, by adding the volumes of all dbh classes in a stand together, an estimate of gross growth is obtained, as follows:

$$GG = \sum T_i (V_i) \qquad (2)$$

where GG is gross growth, excluding mortality, T_i is change in number of trees, and V_i is average tree volume.

To convert the estimate of gross growth into corresponding estimates of net growth, a mathematical function describing tree mortality as a function of the 5-centimeter dbh classes is introduced into the model, as shown by:

$$NG = \sum T_i (V_i) - M_i \qquad (3)$$

where NG is net growth and M_i is mortality.

The computations in STAND are similar to those of the basic stand table projection method described by Meyer (1953), with one important exception. The ratio of cumulative numbers of trees in adjacent 5-centimeter dbh classes is employed to calculate de Liocount's "q" in STAND, while "q" equals the ratio of numbers of trees in adjacent 5-centimeter dbh classes in many other stand table projection techniques.

INPUT REQUIREMENTS

Input requirements to STAND include:

1. site class,
2. individual tree volumes for each 5-centimeter dbh class, and
3. a stand table of growing stock by 5-centimeter dbh classes.

Average annual rates of diameter growth by 5-centimeter dbh class are stored in the model in reference to site class. Individual tree volumes for each 5-centimeter dbh class, obtained through localizations of standard volume tables (Barger and Ffolliott 1972, Chojnacky 1985), also are stored in the model. A stand table of growing stock by 5-centimeter dbh class, for the stand in question, is entered directly from a computer terminal.

MORTALITY FUNCTIONS

Mortality functions that describe tree mortality in relation to 5-centimeter dbh classes have been incorporated into the formulation of STAND to convert estimates of gross growth to net growth. These mortality functions were derived from inventories of the pinyon-juniper and oak woodlands.

REGENERATION FUNCTIONS

Source data are not available to develop regeneration functions that describe the rate of movement of trees into the 5-centimeter dbh class, the smallest dbh class considered. Therefore, it has been assumed that the number of trees moving into the 5-centimeter dbh class will not change appreciably over the relatively short projection periods in STAND. The number of trees initially entered into the 5-centimeter dbh class remains constant throughout a simulation exercise. This assumption has been verified, to some extent, by the literature and on-site measurements in pinyon-juniper and oak woodlands.

SIMULATION OF INITIAL CONDITIONS

To simulate the growth and yield of a woodland under initial conditions, a stand table representing these conditions is projected for a one year period, using the appropriate variables to structure the simulation exercise. The resultant output, including stand and stock tables and basal area distributions, provides a "snap-shot picture" of the initial conditions of the stand being considered.

At the completion of the above simulation exercise, a user may decide to either terminate the exercise, project the growth and yield to some point in the future, or evaluate the changes in growth and yield after the implementation of a land management change in the stand.

SIMULATION AT SOME POINT IN THE FUTURE

Net growth is accumulated "on the stump" during a projection period to simulate the growth and yield of a woodland stand at some point in the future. Mensurationally, for each 5-centimeter dbh class in the stand table, net growth in terms of number of trees is obtained by:

$$NG_T = \frac{NG_V}{V} \qquad (4)$$

where NG_T is net growth, in number of trees; NG_V is net growth, in volume; and V is volume of trees in the ith 5-centimeter dbh class.

For each year in a projection period, a stand table representing conditions at the start of a year is adjusted to reflect growth during the year through solutions of equation (4) for each 5-centimeter dbh class, as shown by:

$$T_e = T_o + NG_T \qquad (5)$$

where T_e is number of trees at the end of a year and T_o is number of trees at the start of a year.

In the current version of STAND, the maximum projection period arbitrarily has been set at 10 years. However, outputs for longer projection periods can be obtained through a "reinitialization" of the outputs at the end of 10 years to represent the initial conditions for the start of a second projection.

SIMULATION AFTER IMPLEMENTATION OF A LAND MANAGEMENT CHANGE

In simulating the growth and yield of a pinyon-juniper or oak woodland stand after the implementation of a land management change, the basic projection technique outlined above is employed, with one difference. A change in land management practices can be expected to affect the diameter growth rates of residual trees. Therefore, the relationships that describe average annual rates of diameter growth are "adjusted" to account for the combined effects of site qualities, intensities of land management change, and years since the land management change.

The adjustments are obtained through modifications of the regression coefficients that quantify the average annual rates of diameter growth by 5-centimeter dbh class, as follows:

$$b_{adj} = b_o + (f_1 f_2 f_3 (b_{max} - b_o)) \qquad (6)$$

where b_{adj} is adjusted regression coefficient; b_o is regression coefficient representing conditions before a land management change; f_1 is impact ranking value of site quality, from 0 to 1; f_2 is impact ranking value of the intensity of land management change, from 0 to 1; f_3 is impact ranking value of years since the land management change, from 0 to 1; and b_{max} is regression coefficient representing "maximum response" conditions.

The "impact ranking values" are specific in terms of a tree species and a woodland type. Site quality is defined by site index values (Chojnacky 1986). Intensity of land management change in terms of changes in diameter growth rates of residual trees is dependent largely upon the initial density of trees and the severity of treatment. The impact of years since the land management change is dictated by the "longevity" of the treatment effect.

Using the adjustments in the average annual rates of diameter growth by 5-centimeter dbh class, and assuming the tree volumes will not change significantly due to a land management change, simulations of the growth and yield of a woodland after the implementation of a land management change are obtained. Input requirements to this option of STAND are the prescribed residual stand table and the number of years since the land management change.

APPLICATION OF MODEL

To illustrate the application of STAND to estimate the growth and yield of a woodland stand in the Southwest, a 48-hectare pinyon-juniper woodland stand on the Beaver Creek Watershed in north-central Arizona will be examined. This example will simulate the growth and yield of a commonly encountered tree species, Utah juniper, under initial conditions, and 10 and 20 years in the future.

It should be stated that, as operated in the Southwest, the units of measurement in STAND are in the English system. These units of measurement have been converted to their corresponding metric system equivalents for presentation in this paper.

SIMULATION OF INITIAL CONDITIONS

A user responds directly to a set of interactive statements and questions that structure the simulation exercise and describe the initial conditions. As the first step, the user responds to questions asking WHICH TYPE? and WHICH TREE SPECIES? PINYON-JUNIPER WOODLANDS and UTAH JUNIPER were entered, respectively, as shown in Figure 1. Next, the user replies to a request to WHAT SIMULATION OPTION? As this part of the simulation exercise is concerned with the growth and yield under INITIAL CONDITIONS, the user responded, accordingly.

The next question asked is WHAT IS SITE CLASS? This input is necessary because the average annual rate of diameter growth is related to site class. In terms of the pinyon-juniper woodlands, three site classes have been delineated, based on arbitrarily specified ranges in site index values (Chojnacky 1986). In this example, SITE CLASS II was entered, as illustrated in Figure 1. To enter a stand table, the user is asked WHAT IS THE MINIMUM 5-CENTIMETER DBH CLASS? and WHAT IS THE MAXIMUM 5-CENTIMETER DBH CLASS? Inputs of 20 and 80, respectively, have been made in this example. After bracketing the stand table, the user must, FOR EACH 5-CENTIMETER DBH CLASS, ENTER NUMBER OF TREES PER HECTARE.

Given the input variables representing the initial conditions, the growth and yield of the Utah juniper trees growing in the 48-hectare woodland pinyon-juniper stand are summarized in Figure 1.

SIMULATION IN THE FUTURE

At this point in the simulation exercise, the user is asked ANOTHER SIMULATION OPTION? The exercise can be terminated by a negative response. However, in this example, a positive response has been made to simulate the growth and yield of the Utah juniper trees 10 and 20 years in the future.

Forest type, tree species, and site class remain unchanged in a simulation exercise to estimate growth and yield in the future. Therefore, the only request made of the user is to ENTER YEARS SINCE START OF SIMULATION. In the example presented in this paper, 10 years was entered as growth and yield 10 years in the future is the first step in this phase of the simulation exercise.

Simulation of growth and yield 20 years in the future also is needed. To achieve this prediction, the outputs representing the conditions at the end of 10 years are "reinitialized" to represent the initial conditions for the start of a second 10-year simulation period, 20 years in the future.

RELIABILITY OF MODEL

The reliability of STAND in simulating the growth and yield of Utah juniper trees can be demonstrated by comparing the results of the

```
STAND: OVERSTORY GROWTH AND YIELD MODEL
 TYPES ARE:
   1 - MIXED CONIFER FORESTS          2 - PONDEROSA PINE FORESTS
   3 - PINYON-JUNIPER WOODLANDS       4 - OAK WOODLAND
 WHICH TYPE? 3
 TREE SPECIES ARE:
   1 - UTAH JUNIPER                   2 - PINYON
   3 - ALLIGATOR JUNIPER              4 - ONE-SEED JUNIPER
   5 - PONDEROSA PINE                 6 - GAMBEL OAK
 WHICH TREE SPECIES? 1
 SIMULATION OPTIONS ARE:
   1 - INITIAL CONDITIONS             2 - FUTURE
   3 - AFTER MANAGEMENT CHANGE
 WHAT SIMULATION OPTION? 1
 SITE CLASSES ARE:
   1 - SITE CLASS I                   2 - SITE CLASS II
   3 - SITE CLASS III
 WHAT SITE CLASS? 2
 WHAT IS MINIMUM 5-CENTIMETER DBH CLASS? 20
 WHAT IS MAXIMUM 5-CENTIMETER DBH CLASS? 80
 FOR EACH 5-CENTIMETER DBH CLASS, ENTER NUMBER OF TREES PER HECTARE
   DBH CLASS             NUMBER OF TREES PER HECTARE
      20                            46.4
      25                            43.2
       .                              .
       .                              .
       .                              .
      80                             0.2
  PER HECTARE VALUES

                   TREES         BASAL AREA        VOLUME
   DBH CLASS      (number)    (square meters)  (cubic meters)
      20            46.4            1.5              7.4
      25            43.2            2.2             10.0
       .              .              .                .
       .              .              .                .
       .              .              .                .
      80             0.2            0.1              0.4

    TOTALS         151.5           11.4             47.6

 ANOTHER OPTION (YES OR NO)? YES
 WHAT SIMULATION OPTION? 2
 ENTER YEARS SINCE START OF SIMULATION (UP TO 10): 10
```

Figure 1. - An example of the application of STAND.

simulation exercise with baseline inventory data. Unfortunately, only limited inventory data are available to characterize the growth and yield of Utah juniper trees in the pinyon-juniper woodlands in the Southwest. However, one set of available data was obtained on the same 48-hectare pinyon-juniper woodland stand considered in the simulation exercise.

For the pinyon-juniper woodland stand of concern, the growth and yield of Utah juniper trees were estimated from remeasurements of 42 permanently located sample points (Pollisco 1987). The sample points were established and initially measured in 1965 and then remeasured in 1985. From these measurements, estimates of net annual increment and volume were derived, both of which were compared subsequently to the corresponding simulated values. Importantly, the simulation exercise of this pinyon-juniper woodland stand was structured to represent the same time periods as the inventory. That is, the initial conditions in the simulation exercise represented the measurements made in 1965, with the simulated conditions 20 years in the future representing 1985.

Net annual increment for the 20-year period, based on remeasurements of the pinyon-juniper woodland stand, was 0.15 ± 0.029 (mean ± SE) cubic meters per hectare, while the simulated net annual increment for the same 20-year time period was 0.17 cubic meters per hectare. The remeasured volume in 1985 was 50.5 ± 10.1 (mean ± SE) cubic meters per hectare, and the simulated volume in 1985, representing 20 years in the future, was 51.1 cubic meters per hectare. In both instances, the reliability of STAND was considered acceptable.

Although less stringent, another "test of reliability" of the simulated net annual increment value was based on published reports of the growth of Utah juniper in a study area located near the Beaver Creek Watershed. Ten-year and 20-year growth records of Utah juniper trees on a 1.6-hectare sample plot located close to Sedona, Arizona, approximately 25 kilometers from the Beaver Creek Watershed, were reported by Herman (1953) and Myer (1962), respectively. Gross annual increment and ingrowth were greater for the 20-year period than for the initial 10 years. However, because mortality also was greater, net annual increment was the same for both periods, averaging 0.21 cubic meters per hectare.

As the trees measured on the sample plot included all stems 10 centimeters dbh and larger, smaller trees were included in this study than considered in the illustrative simulation exercise. Unfortunately, it is impossible to mensurationally "adjust" the reported net annual increment to compensate for the differences in dbh classes, although a reduction in the reported net annual increment appears justified. Such a reduction, if it could be made, might result in "closer agreement" between the reported net annual increment and the simulated net annual increment of 0.17 cubic meters per hectare.

SPECIFICATIONS OF MODEL

STAND is a generalized growth and yield computer simulation model for forest and woodland types in the Southwest. The types considered are the mixed conifer forests (a forest type comprised of seven coniferous and one deciduous tree species), ponderosa pine forests, and as reported herein, the pinyon-juniper woodlands and oak woodlands. It has a modular format, with a user-friendly interface for data entry. STAND is written in the FORTRAN/77 computer language, using a DOS 3.0 operating system.

STAND, designed for application on microcomputers, is adaptable to many IBM compatible machines. The model has a minimum memory requirement of 100K, and it can be executed from either a single floppy disk or hard disk drives.

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USING MICROCOMPUTERS TO NARROW THE GAP BETWEEN RESEARCHER AND PRACTITIONER: A CASE HISTORY OF THE TVA YIELD PROGRAM

Todd E. Hepp

ABSTRACT. The TVA YIELD (Timber Yield Forecasting and Planning Tool) microcomputer program performs growth, yield, and financial analysis for even-aged forest types of the southeastern United States. The user-friendly format permits non-researchers to tap into research results comprising 42 separate publications which are summarized as a family of 13 individual simulators. Since its introduction in 1981, YIELD has matured through four revisions and has been distributed to a diverse audience of several hundred users. Based on these experiences, we present a discussion on the growth and yield technology transfer process in general, and the use of software in particular. Applications cited include nonindustrial private landowners, industrial landowners, national forest planners, researchers, educators, investors, regulatory agencies, and others.

INTRODUCTION

Growth and yield research results for southern U.S. forest types have accumulated over the past half century into a collection of several hundred publications (Alig, 1984). Unfortunately, wide technology gaps have evolved between this valuable information base and a large group of potential users. As recently as 1980, there was little evidence that consulting, State, and Extension foresters who manage the vast non-industrial private forests (NIPF) of the southern U.S. were making effective use of contemporary growth and yield prediction technology. The problem was primarily because of limitations imposed through use of printed media to convey research results in the form of inflexible yield tables. Excessive technical jargon, segmented publications, and lack of integration with financial analysis also restricted use of growth and yield research results. Our goal was to overcome these shortcomings through development of a powerful yet friendly software program.

Since the introduction of microcomputers in the late 1970's we have witnessed phenomenal increases in microcomputer capabilities accompanied by continued reductions in costs. Word processors, spreadsheets, databases and other commercial software products have proliferated into tools for everyday use by many forest managers. Likewise, vertical market software products have evolved for many professions including forestry (FORS, 1987). YIELD 1.1 (Hepp, 1982) was the first microcomputer-based growth

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and yield program introduced in the U.S. Since then we have come to regard software as a potent yet cost effective growth and yield technology transfer medium. Economy of scale benefits offset the high costs for developing software. Valuable research results comprising reams of publications are concentrated on inexpensive diskettes and duplicated for mass audiences. Users in turn can now target sophisticated growth, yield, and financial analyses for specific applications to fill long-standing information voids. These changes have all taken place rapidly and the sudden surge in use has not been without problems. This report discusses the technology transfer process before focusing on YIELD's justification, operation, implementation, applications, and future possibilities. The discussion should be of value to those considering development of similar types of software for other regions or countries.

GROWTH AND YIELD TECHNOLOGY CONTINUUM

Growth and yield research results are a means to an end. That end generally is some appropriate on-the-ground-activity. To better understand the entire process it is helpful to visualize information transfer as a continuum (Figure 1). The steps listed in Figure 1 are typical for NIPF work, but represent one of many possible arrangements. Note that a research publication (step 10) is only an intermediate step in the entire information transfer scheme. Only large corporations or agencies have the scope of vertical diversification required to span the entire continuum. Even in large organizations it is likely that transfer of information involve several major divisions within the organization. Information invariably changes hands many times before reaching the landowner/decision maker.

ACTIVITY	**ORGANIZATION**
1. Identify growth and yield information void	Funding
2. Gain support and funding for study	V
3. Develop study plan and sampling scheme	Research
4. Locate and install plots	V
5. Collect and record data	Cooperator
6. Enter data into computer	¦
7. Edit data	V
8. Select a modeling scheme	Research
9. Fit and test equations	¦
10.Publish results	V
11.Implement results in computer software	Software Dvp.
12.Distribute program, support users	Clearinghouse
13.Train end user	User Org.
14.Apply software in forest planning process	User
15.Appropriate on-the-ground-activity	Landowner

Figure 1. Growth and yield technology development continuum

JUSTIFICATION

Our primary motive for developing YIELD was to provide a potent yet easy-to-use NIPF landowner decision-making tool for estimating financial returns on various forest management practices. We believed that custom prepared, return on investment information should motivate individual landowners to invest in reforestation, thinning, and other cultural practices deemed appropriate by the analysis. Financial return is not always the primary incentive for holding forest land but it usually is the motive for investing in management practices. Some of the variables which influence rate of return for forestry practices include the strength of local wood markets, species grown, site quality, tax effects, harvest frequency, timing, method and intensity, and the availability of subsidy payments. YIELD uses the computational power of the computer to analyze this complex mixture of data into concise output that is readily understood by the landowner.

The NIPF sector is of particular concern to TVA because it comprises three/fourths of the forested acres in the southern U.S. The multibillion dollar forest products industry depends on this resource for a raw material supply. The resource also provides wildlife habitat, recreation opportunities, and watershed protection. Studies by Knight (1987), and Sheffield and Cost (1987) report that the NIPF sector is lagging behind in reforestation efforts on pine sites, thus threatening the level of industry activity for the future. Forest stand quality (tree size, species, and form) also has deteriorated from poor cutting practices. NIPF landowners in the U.S. are largely unregulated, therefore information dissemination is the primary tool available to government to help reverse such rural development problems.

OPERATIONS

YIELD is a stand level model for evaluating even-aged stands. It directly integrates growth and yield simulations with financial analysis (Figure 2). YIELD has evolved through four versions over a six year period. A new version called YIELDplus 1.1 is scheduled for distribution beginning October, 1987. Although the capabilities of YIELD have grown with each new version, the original basic design remains intact. Selection of features added to each new version is guided by user suggestions combined with ideas initiated by the developer. A successful software package requires a commitment by the developing organization to keep pace with changing computer technology. Computer hardware and software industry standards change rapidly. To remain practicable, YIELD also has had to keep pace with changing subject matter. For example, each year growth and yield researchers publish new results and the Internal Revenue Service (IRS) frequently revises tax regulations. Technical support for users also is crucial because a user who cannot operate a program quickly becomes discouraged.

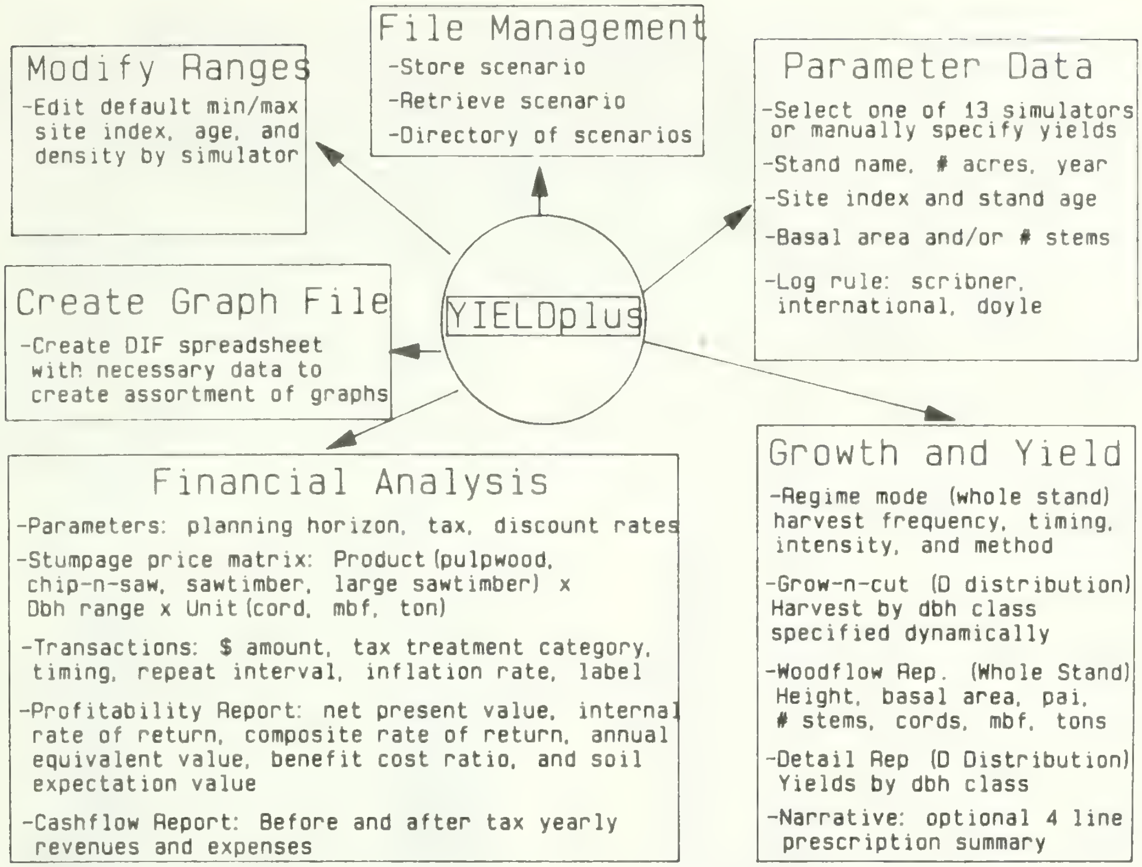
YIELDplus
Modify Ranges
-Edit default min/max site index, age, and density by simulator
File Management
-Store scenario
-Retrieve scenario
-Directory of scenarios
Parameter Data
-Select one of 13 simulators or manually specify yields
-Stand name, # acres, year
-Site index and stand age
-Basal area and/or # stems
-Log rule: scribner, international, doyle
Create Graph File
-Create DIF spreadsheet with necessary data to create assortment of graphs
Financial Analysis
-Parameters: planning horizon, tax, discount rates
-Stumpage price matrix: Product (pulpwood, chip-n-saw, sawtimber, large sawtimber) x Dbh range x Unit (cord, mbf, ton)
-Transactions: $ amount, tax treatment category, timing, repeat interval, inflation rate, label
-Profitability Report: net present value, internal rate of return, composite rate of return, annual equivalent value, benefit cost ratio, and soil expectation value
-Cashflow Report: Before and after tax yearly revenues and expenses
Growth and Yield
-Regime mode (whole stand) harvest frequency, timing, intensity, and method
-Grow-n-cut (D distribution) Harvest by dbh class specified dynamically
-Woodflow Rep. (Whole Stand) Height, basal area, pai, # stems, cords, mbf, tons
-Detail Rep (D Distribution) Yields by dbh class
-Narrative: optional 4 line prescription summary

Figure 2 YIELD summary of operations (YIELDplus version)

IMPLEMENTATION

TVA began distributing YIELD 1.1 in 1981. Version 1.1 executed on a Texas Instruments (tm) DS990 microcomputer. This was soon followed by version 1.2 which included several refinements and CP/M compatibility. Hepp and Field (1982) prepared version 2.1 for internal use by the Southern Region of the U.S. Forest Service. Version 1.3 followed in 1984 with significant improvements to program operations and IBM PC compatibility. In 1985 version 1.4 was released. Vodak (1986) published a technical evaluation of YIELD comparing it to other financial analysis software. Development of a related program called TIMPRO (Hepp and Williamson, 1986) was completed one year later. The YIELDplus version we are developing now marks the most radical enhancements to date.

Initially, TVA staff processed requests for the program and provided technical support. Beginning in 1984 however, the Forest Resources Systems Institute (FORS) became the sole distributor of the program, thus alleviating the distribution and support burden from the development team. YIELD is part of the public domain but FORS distributes and supports it in exchange for a modest fee. FORS records of program distribution were used as a base for conducting an informal telephone inquiry of users. We grouped users according to the following types: Consultants (Con), Financial Organization (Fin), Industry (Ind), Landowner (Lnr), Miscellaneous (Msc), National Forest System (NFS), Other Federal Government (Otr), State Forestry Divisions (Sta), International (Int), and University & Extension (U&E). Since large organizations distribute multiple copies of the program to remote locations, we report distribution according to number of installations. The data do not account for unregistered copies of the program nor multiple users of single computers.

Of over 600 installations recorded, the greatest number occurred in the university & extension category. Georgia leads all States for the greatest number of installations followed by South Carolina (Figure 3). These results are attributed to aggressive distribution by the Cooperative Extension Service. Since YIELD contains growth and yield research results for Southern U.S. timber types it is no surprise that Southern pine belt users request the most copies (Figure 4). There also are 13 international users.

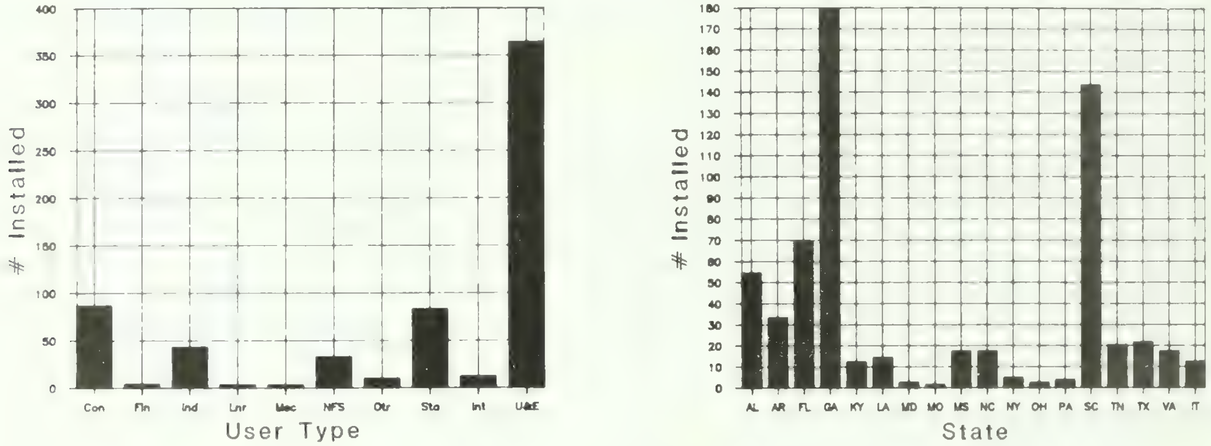

Figure 3. YIELD installations by user category and State

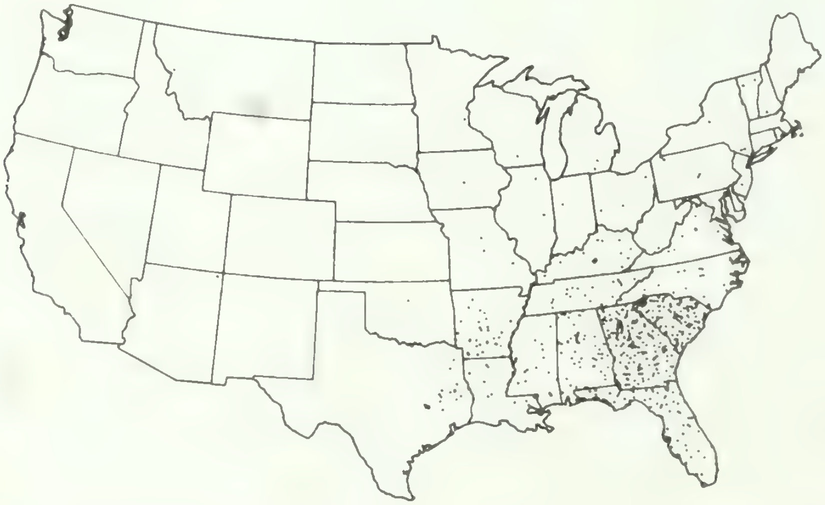

Figure 4. YIELD installation locations in the U.S.

We estimated intensity of use by posing to those sampled the question "how many acres have you evaluated with YIELD"? State and Extension groups keep good records of management plan preparations and were able to estimate the number of acres evaluated with reasonable certainty. Industry users were reluctant to estimate acres and suggested that the program is used more to form policy about the management of large company tracts rather than make decisions for individual stands. The consulting forester group had the greatest variation in use. Since this category had over 80 users, we questioned a random subsample of 10 consultants.

Although university & extension had the largest number of installations, the consultants category accounted for the greatest number of acres. Alabama evaluated the most acres for a State (Figure 5) attributable to extensive use by the Alabama Forestry Commission. We did not include the number of NFS acres in Figure 5 because the group's size (13 million acres) would tend to "wash-out" the other categories. We estimate 16 million acres have been evaluated by YIELD to date including NFS lands. The number of acres evaluated is not a measure of on-the-ground-activity. However, there are several studies which document cause and effect relationships between technical advice and landowner activity (Cubbage et al. 1985), (Straka et al. 1986).

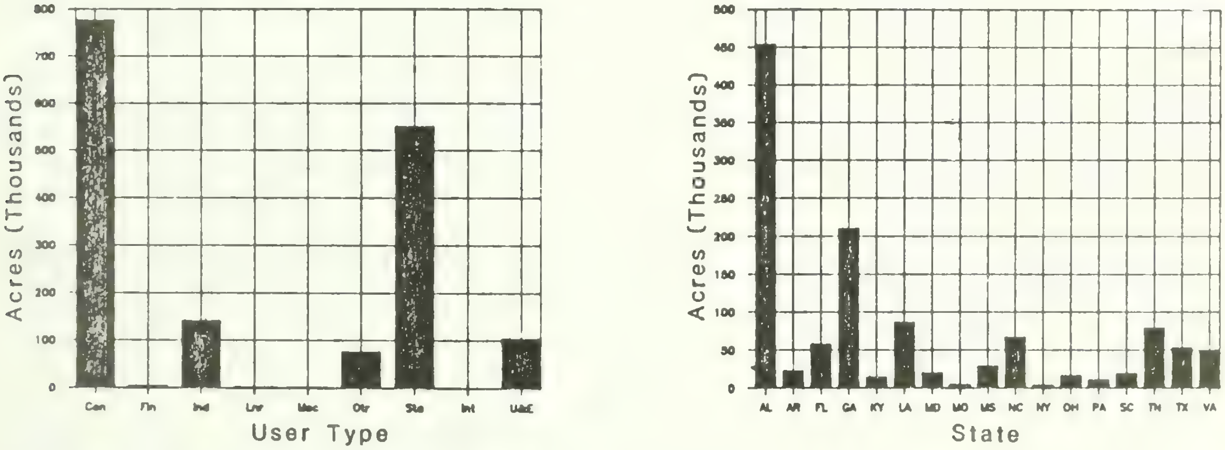

Figure 5. Acres evaluated with YIELD by user category and State

APPLICATIONS

Consulting foresters use the program most intensively, to prepare growth, yield and investment analysis information for their clients. YIELD provides the hard numbers necessary to convince a landowner to invest capital in reforestation, thinning, and other cultural practices. University and extension foresters use the program for the same basic purposes. In one State, county agents with agricultural backgrounds are trained to use YIELD in order to illustrate to individual landowners the pros and cons of forestry along with those for row crops, grazing, and other alternative land uses. In this vein, YIELD also has been used to prepare press releases and to quantify annual financial returns for tree farming versus row crops for various soil types (McKee, 1986). YIELD quantifies return on investment for tree farms planted on highly erodable land and is valuable for promoting the Conservation Reserve Program. In effect, YIELD is a selling tool for forestry.

YIELD has been used for other purposes not originally envisioned. For example, the IRS acquired a copy to help verify tax returns and the Department of Defense uses it for managing extensive forest lands on military bases. Instructors at many universities use it to illustrate forest stand dynamics and financial analysis concepts. Several banks and investment firms use it to screen institutional forestry investments. Researchers have used YIELD to simulate the effects of various cultural practices. The National Forest System (Southern Region 8) has made extensive use both for FORPLAN runs and for prescriptions on individual stands. In a few instances, landowners who have a basic understanding of forestry and microcomputers use YIELD to evaluate their own land.

The sudden heavy use of growth and yield technology spawned by the abundance of microcomputers has among other things exposed the shortcomings of both models and their users (Hepp, 1987). Users who are insensitive to model limitations or who lack knowledge of financial concepts run the risk of making faulty inferences. Misapplication of the program can lead to bad advice and expensive mistakes. Adequate training in both theory and mechanics is essential for successful use. Just as software advances have failed to keep pace with hardware advances, users have failed to keep pace with software advances. Some forest managers are wary about using mathematical models, especially when the mathematical models give output which conflicts with mental models. Lack of relevance, inadequate training, and the unavailability of computers also may restrict use.

CONCLUSION

Microcomputer software is the most effective medium now available for applying growth and yield research results. YIELD marks a pioneering effort but the medium still has a long way to grow. As technology permits, the user interface for programs such as YIELD should become more visual through de-emphasis of numeric output in favor of multi-colored, high resolution graphics, diagrams and pictures. Hardware advances such as battery operated laptop computers promise to reduce costs and increase client responsiveness by permitting one-stop management plan preparation on the site. A successful software package requires a continuing commitment by a sponsoring organization. To remain viable, a program must be kept: 1)relevant to the information needs of the users, 2)current to latest regulations, technology and research results, 3)operable on popular hardware configurations, 4)friendly through contemporary user interfaces, and 5)supported so that it can be easily installed and operated. Failure to keep pace with any of these aspects of maintenance can seriously compromise success. Regardless, the training level of the user probably is still the most limiting factor to completing the information transfer process.

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WHAT GROWTH MODELS ARE NEEDED FOR FOREST MANAGEMENT IN CANADA?

Joe J. Lowe[1]

ABSTRACT. Growth and yield estimates are critical to the manager's models of the forest and the need to predict results in reaction to possible scenarios.

Suitable growth and yield estimators are not universally available, and few researchers or managers seem to recognize the full range of applications.

The paper outlines the major applications and deficiencies perceived in Canadian forestry.

INTRODUCTION

This forum on the research and use of growth models is designed for a wide audience. The organizers expected a mixture of "researchers, forest managers, administrators, consultants, and others ..."

If this eclectic groups is to update each other effectively, it requires a reasonable understanding of where growth models fit into forest management. Holistic site-specific forest management is the client discipline that justifies society's investment in growth modelling.

This paper is addressed to all present. It is generic about modelling needs, and also deals with equally important aspects of forest management.

The desire to present the paper arose from some personal observations in North America in general, and Canada in particular. These observations indicate common situations although, like most general observations, they do have notable exceptions.

a) Forestry is no longer a matter of finding and harvesting enough wood within acceptable limits of environmental damage. The limited renewable resources must now be managed more intensively, with consideration of many costs and benefits. There must be better prediction of results and audits of performance.

b) The technology to gather and process information, and to create models, is evolving rapidly.

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c) There is often an inadequate professional understanding of modern forest management and management planning. In Canada there are many reasons for this, chief among them being an initial preoccupation with the exploration and development of a large frontier resource. Another major reason is the jurisdictional balkanization of forest management and research into relatively small, and often overextended, forestry agencies.

d) There are often serious organizational inhibitions to the development of experienced and authoritative on-site forest managers.

e) Senior managements have generally provided inadequate foresight and support for the research and DEVELOPMENT of practical growth models.

f) There is too much growth research that is not appropriate, or appropriate research that has not been applied.

g) There are too many forest managers who do not, or cannot, articulate their information needs, and too many information systems which do not deliver what is needed.

THE MANAGER AND THE MODELS

The manager of the forested estate is arguably the most important person in forestry, and should be thought of as the prime client for growth modellers. Timber is only one aspect of forest management although, in Canada, it is economically the most important and has the best information base.

The manager's basic responsibilities are to predict results, evaluate options, plan and perform operations, observe and record activities and change, monitor results, and improve predictions. It begins and ends with PREDICTION. Anything less than this is not forest management. In Canada there is a wide range of situations, but most managers aspire to these functions, at least in public.

The ultimate dream of a forest management information system would be a dynamic model of the forest in a dedicated computer. The dream system could answer any question in time or space about the forest and the effect of any activities. The system would be accurate and comprehensive, and could handle futuristic forest types and activities which have not yet been experienced. It could respond to any standard of utilization and any scale of value. It could handle all aspects of forest management, not only timber.

Dreams of perfection are unlikely to be practicable or even desirable, given the levels of detail and costs involved. The trick is to agree on the practical optimum for the particular situation.

Fortunately, several good model systems are starting to appear. They can be applied to particular situations directly or with modification. The component functions of growth and mortality will obviously need localizing.

Unfortunately, one can expect many misapplications of these systems. The chief mistake will be the failure to assess fully the characteristics of the model and the situation of application.

THE PRESENT SITUATION IN CANADA

Most Canadian forest managers need, or will soon need, better growth information. There is a rising interest in growth studies, especially in western Canada.

Forest managers and senior management are no longer satisfied with a static forest inventory that identifies the harvest for the next 20 years, nor with rudimentary volume/age curves used only to select a rotation length and to calculate an allowable cut.

Geographic information systems offer automation of mapping. Forest managers are exploring the development of forest management information systems in which a dynamic inventory can be handled electronically in time and space. To appreciate the significance of this one should realize that Canada's forest inventories collectively cover about 44 000 map sheets, and perhaps 10 to 20 million type islands (stands).

The further significance is that management calculations can now be done at the stand level, not only with some bottom line stratum totals. The stand level calculations respond better to local variation, even if individual stand estimates are suspect and must be aggregated for reasonable confidence.

The Canadian forest manager now sees a break from the drudgery of handling maps and numbers, and a chance to use the available information in an effective forest management information system. There are increasing expectations of this power being in the hands of field staff, and not restricted to headquarters specialists.

Prototypes of this capability already exist in Canada in the more advanced agencies. Most provincial forestry services, and some companies, are well advanced in the acquisition and loading of geographic information systems, and are actively exploring ways to use the information to meet their own management needs. The Canadian Forest Inventory Committee has identified the shortage of good growth models as a major problem - even the provinces with the best growth information are not satisfied with their situation.

At the strategic level, Canada's latest national forest inventory (1986 version) will be overlaid with the best available national growth information. The growth data are as reported by Bickerstaff, Wallace, and Evert (1981), with certain subsequent upgrades from provincial sources. The combination of inventory and growth rates will, improve estimates of the country's forest productivity. Unfortunately the estimates can only be given for mean annual increment of the existing forest for all species combined. It will not be possible to report current increment, nor to disaggregate the data reliably below the provincial level. This is because most existing growth information is specific to location and forest condition, and was not designed to mesh with a standardized national inventory.

THE NEEDS

BASIC COVERAGE

The first need is for basic and reasonably reliable growth and yield models that meet certain criteria.

a) They can be applied to the EXISTING forest inventory.

b) They are available for ALL existing forest conditions.

c) They predict gross merchantable volume over time.

d) They can be used to suggest an optimum rotation.

Many published growth and yield models or tables fail to meet these criteria, and are virtually useless to the forest manager. He is better off with a freehand curve drawn through what experience tells him is a typical merchantable volume at maturity. The manager needs quick and dirty models today while waiting for tomorrow's improvements.

RESEARCH

The second need is for basic research into two very different but equally important areas.

a) How do forests grow, and how can they best be modelled?

b) Exactly what growth models are needed for forest management in the foreseeable future? In Canada this will require better coordination between forest management and research agencies concerning the science of forest management and its service information disciplines (inventory, growth modelling, etc.). Although these studies should be geared to the Canadian situation, they should in no way be isolated from international experience. Forest management must also concern itself more with economics, especially on Crown lands. "Today's foresters can and must be forester-economists" (Miller, 1987), and the models must be capable of serving this discipline.

UPGRADED COVERAGE

There will be a continuing need to upgrade the initial basic models as opportunity presents itself, with consideration of users' priorities and sensitivity analyses. These upgrades could involve many areas of improvement.

a) To mesh with improved forest inventories and site classifications.

b) To be more location specific and more accurate.

c) To respond better to varying product utilization specifications. Many parts of Canada are seeing dramatic changes into more intensive utilization.

d) To predict stand structure, especially volume, basal area, and frequency by species and size distribution. Other parameters will be needed that relate to non-timber products and their values.

e) To handle changes in stand composition and density over time. These changes will be natural processes and/or human manipulation.

f) To handle the continuum of actual stand conditions. These actual conditions are not necessarily what was intended, and will range from silvicultural slums to dream plantations. It is not enough for growth modellers to consider only two forest conditions, "unmanaged" and "managed".

g) To predict regeneration response (Dickinson, 1987).

h) To handle the most probable situations of natural change and human intervention in the existing and future forest conditions. This is a Pandora's box of possibilities, and will involve the biological models mentioned later.

Models to fit all possible situations may not be justifiable, and human judgment may still be the default model. To mention the major topics shows how complex they are, especially because they may be interdependent. For example, these models could be expected to handle all the major forest pests and other agents of damage, with various levels of intensity from control to endemic to epidemic or catastrophic. Other topics include site treatment and fertilization, weeding, thinning, and the use of improved or exotic species.

BIOLOGICAL MODELS

Many claims are made for the benefits of more intensive forest management. This suggests a need for what can best be called "biological models" for the major commercial tree species. These would model certain aspects of the biology of the tree or stand in order to predict development in response to such silvicultural activities or fertilization, spacing, and thinning.

These biological models would be used off-line from the inventory-based forest management information system. They would be used to predict the effects of silviculture, and to assess the costs and benefits of those expensive activities. Once desirable silvicultural options had been selected, the biological models would be used again to generate "conventional" stand development models for those options.

The "conventional" models would be loaded into the forest management information system, for use by the forest manager when he selected the viable option appropriate to his situation. The default option should always be "no treatment or harvest".

EVALUATION OF MODELS

In this jungle of model improvement there will be hyper-salesmen and confused consumers, so evaluation of growth and yield systems will be extremely important. Buchman and Shifley (1983) outline the principles of evaluation.

Walker (1987) points out that when selecting models there must be a balance of "transparency, generality, accuracy and precision". He adds that model adequacy is subjective, and should be determined by, or at least in close association with, the accountable managers. The key is for the model to "adequately represent the forest system", and for the manager to see the model's abstractions "as analogs of practicable solutions to the actual problem".

THE MANAGER

There is a need for the creators of stand development models to make their products as robust and "transparent to the user" as possible, but they should not aim to make them foolproof. Foolproof products are for use by fools.

The forest manager must be aware of the basic implications of the models in use, and must have a professionalism appropriate to such sophisticated information. Professionalism can only come from good training and experience. Forestry is applied biology as well as applied engineering and economics, and biological experience involves a strong element of local experience. The best model cannot absolve the model used from the need for local experience and professional judgment. The user must understand the logic, if not the processing details, within the black boxes.

The Director of Timber Management for New Brunswick has said that developing the database for the forest manager should "make decision making more difficult because it should expose previously unidentified options". He also lays a clear charge on the manager and the modeller when he puts "the decision maker's (manager) neck on the line by demanding unequivocal and measurable statements of what the precise outcomes of specific actions are intended to be" (MacFarlane, 1987).

The best advice to the manager, the modeller, and the measurer would seem to be: hang together or hang separately.

This leads to one more need, the need to overcome the popular misconception that better information and information processing are the technical fix for all problems. They cannot work by themselves. Senior management should recognize several things.

a) Forest managers need clear objectives. In Canada most of the commercial forest is on Crown land. Davis and Johnson (1987) comment shrewdly that public forest land managers tend to "have poorly defined guidance" as to goals.

b) Forest management is not an instinctive art, but is a science that is in need of more research, education, coordination, and development.

c) Forest inventory and growth modelling are essential service disciplines that need similar nurturing, but that should follow rather than lead in the dance of forest management.

SUMMARY

The ability to predict is at the heart of forest management.

Modern technology and expectations suggest sophisticated but robust computerized forest management information systems. These should be capable of handling time, space, economics, and many management options.

This evolution is underway in Canada, and there is a rising need for appropriate growth models.

The first need is for basic comprehensive coverage with useable growth models that predict merchantable volume and can be applied to the current inventory.

Research is needed into the modelling of forest growth, and to find out what models are needed.

There will be a continuing need for upgrading of the basic coverage to become more accurate and to handle the increasing complexity of management expectations.

Biological models will be needed to mimic the forest's response to human and other activities, especially for situations which do not yet exist for empirical observation.

Models must be carefully evaluated in the context of their use.

The science of forest management should be researched and developed more completely in the Canadian context. Forest managers must be developed to possess more professionalism, experience, and authority. The managers need clear objectives, and should themselves lead rather than follow the information disciplines of inventory and modelling.

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AN OVERVIEW OF CACTOS: THE CALIFORNIA CONIFER TIMBER OUTPUT SIMULATOR

Walter J. Meerschaert[1]

ABSTRACT. The computer simulator CACTOS is designed to model the changes that take place in young-growth conifer stands in the mixed-conifer region of northern California. CACTOS requires the user to enter a stand description and allows the user to perform various operations and print out various descriptive reports of the stand. This interactive program is written in standard FORTRAN 77 code. The current version is running on IBM PC compatible personal computers, the Apple Macintosh, and Data General minicomputers. To run the program, the user answers questions or issues two-letter commands. The list of commands available at any stage can be displayed by typing **pc** (for print commands).

INTRODUCTION

CACTOS, the CAlifornia Conifer Timber Output Simulator, is an interactive computer program designed to simulate the growth and partial harvests of conifer forest stands in northern California. CACTOS is designed to provide the forestland manager with a means of predicting the changes that are likely to take place in a young-growth conifer stand, either due to the uninterrupted growth processes or as a result of interventions on the part of the forest manager.

The general structure of CACTOS is illustrated in figure 1. These components are briefly described below and then treated in detail in Wensel, et.al., 1986. The CACTOS program provides the user with a menu from which various operations may be selected to alter the user-supplied stand description. The menu allows the user to: (a) initialize or change the default program parameters which determine the minimum DBH, merchantable top diameter, species groupings, etc. used for summaries; (b) simulate changes in the stand description by growth, harvest, or ingrowth; and (c) prepare reports describing the stand at any point in time.

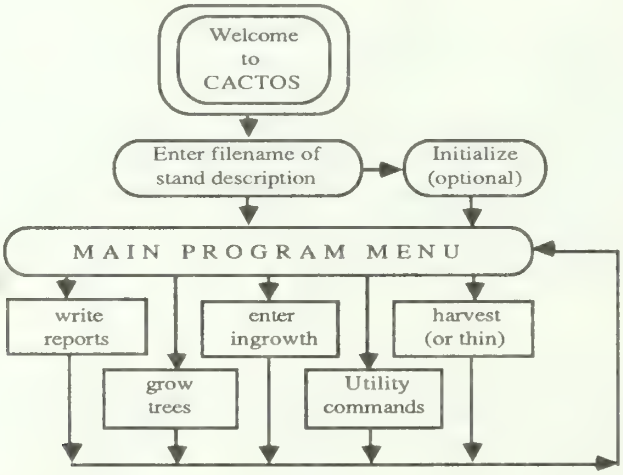

Figure 1. Structure of components of CACTOS

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STAND DESCRIPTION

A stand description consists of the site index and initial age (optional) of each species and a list of the trees representing the stand. The site index is used as a measure of the potential productive capacity of the stand, using the site relationships developed by Biging and Wensel (1985).

Each tree record in the stand description contains the following five items:

(1) a two digit species code
(2) DBH in inches
(3) total height in feet
(4) height to the base of the live crown in feet or live crown ratio
(5) number of trees per acre represented by this tree record

Frequently, the user will want to model a stand without having all of these data items. Thus, external to CACTOS, provision has also been made to "fill in" the missing data using STAG, the STAnd Generator (Van Deusen and Biging, 1985).

MAIN PROGRAM MENU

CACTOS is menu driven to make it "user friendly". The program is operated by either responding to questions from the program, or by typing a two-letter command in response to the main program menu prompt "go:" The list of the commands shown in Table 1 is obtained when the command **pc** (print commands) is typed.

Table 1. CACTOS main menu.

Report Commands

pi - print initial description
sc - print current species group
dt - enter DBH dist. routine
dc - print DBH class table
yd - print yield summary
cg - print current 5 yr growth
pm - print DBH mins & merch tops
su - print user defined sp. group
pf - enter stand profile routine
st - print stock table
sl - print standing log table

Simulation Commands

gr - enter growth routine
ct - enter harvest routine
ig - add ingrowth to tree file
cl - initilize/reset user calibration

File Utility Commands

cf - change output file number
sv - save current stand status
rt - restore stand saved by "sv"
es - external save of current stand
ns - start over with new stand
os - truncate yield summary

ex - exit from program

GROWTH PREDICTION

The actual growth prediction is done in response to the grow command, **gr**. At this point, the program computes the summary stand statistics, computes a density measure for each tree (depending upon the size of the tree in relation to the others in the stand), and accesses the various equations used to predict the changes in the tree characteristics for a user-specified number of 5-year growth cycles (Wensel and Biging, 1987 and Wensel, et. al., 1987). Thus the growth process actually changes the stand representation as given by the tree list. Individual tree growth detail and/or growth summaries for each growth cycle may be requested. Before or after the **gr** command is issued, the user can invoke commands to harvest part of the stand and/or to print out various stand summaries.

CALIBRATION

User calibration of basal area and/or height may be specified. Calibration can be used to adjust the final growth prediction. Such adjustments may be necessary due to silvicultural activities, microsite, or any similar factor not specifically addressed in CACTOS. Users can implement this feature as an option from both the initialization routine and the main program. Calibration schemes are entered either through the keyboard or from an external file. A scheme may be applied at any point in stand growth simulation and for any number of growth cycles. Given this versatility, users can create and apply a variety of schemes. However, the degree of calibration is limited to prevent drastic alterations to the response surfaces of the growth models.

INGROWTH

For short-term simulations of growth, ingrowth (growth of trees to merchantable size) can be provided for by including smaller trees in the original stand description. However, for longer simulations, trees not otherwise provided for in the description may have to be entered to more accurately represent the stand development. These trees can be entered using the ingrowth command, **ig**. This command allows the user to enter tree descriptions from the keyboard or from a specified external file.

UTILITY COMMANDS

Utility commands allow the user to save the current stand description (either internally or externally) for later use. This permits more efficient generation of several alternative prescriptions for a single stand.

HARVEST OPTIONS

Several harvest options provide the ability to perform thinning operations on the stand currently held in the computer memory in much the same patterns that one might harvest stands on the ground. This enables one to compare alternative simulations with the same starting data but with different thinning options.

GENERATION OF REPORTS

Within the main program menu, provision is made to summarize the current stand in different ways. The options available range from a simple list of tree records to a log stock summary or yield/harvest summaries. One summary of particular interest is the **pf** command which displays the current stand profile, showing the average height and crown size by diameter class. Reports shown on the screen can be saved in a report file for later processing. Per-acre summaries of the 5-year growth, ingrowth, and harvest are automatically stored in the yield summary file (see figure 2.)

Figure 2. Sample yield summary file produced by CACTOS

```
    YIELD SUMMARY: units = english
    -------------
    stand label = Demo Data Plot 9-79

                    min. DBH    merch top
        cubic ft.     0.0          4
        board ft.     8.0          6

    species      site   init. age
    Pond. Pine   100.       30.
    Cedar misc    80.       30.
    DouglasFir    90.       30.
    White Fir     90.        0.

 ----------------------------------------------------------------
  species          et   dbar     tpa   basar    cvol   bdvol     bagro    cvgro    bdgro
 ----------------------------------------------------------------
  all pines      0.00  22.42    25.0    68.5    2.38   13.85      0.0     0.00     0.00
  true fir       0.00   6.79   100.0    25.2    0.42    1.09      0.0     0.00     0.00
  doug fir       0.00  18.11    50.0    89.4    2.89   15.77      0.0     0.00     0.00
  Totals         0.00  13.80   220.0   228.6    6.55   34.33      0.0     0.00     0.00
 ----------------------------------------------------------------
  all pines      5.00  23.36    24.7    73.4    2.69   16.12      4.9     0.31     2.27
  true fir       5.00   7.65    84.4    26.9    0.51    1.56      1.7     0.08     0.46
  doug fir       5.00  19.04    48.8    96.5    3.29   18.47      7.1     0.40     2.69
  Totals         5.00  14.94   201.3   245.2    7.44   40.40     16.6     0.88     6.07   M
 ----------------------------------------------------------------
  all pines     10.00  24.30    24.4    78.4    3.01   18.58      5.0     0.32     2.46
  true fir      10.00   8.36    74.7    28.5    0.59    2.08      1.6     0.08     0.52
  resid con     10.00  14.95    42.1    51.3    1.05    4.92      2.9     0.10     0.67
  Totals        10.00  15.95   188.8   261.9    8.36   46.95     16.7     0.92     6.56   M
 ----------------------------------------------------------------
  all pines     15.00  25.23    24.1    83.6    3.35   21.23      5.2     0.34     2.65
  true fir      15.00   9.00    67.9    30.0    0.67    2.53      1.5     0.08     0.45
  doug fir      15.00  20.89    46.7   111.1    4.15   24.49      7.4     0.44     3.12
  Totals        15.00  16.88   179.4   278.8    9.32   53.80     16.9     0.96     6.84   M
 ----------------------------------------------------------------
HARVESTS:  demo harvest                                  growth harvested
 ----------------------------------------------------------------
  all pines     15.00   0.00     0.2   -66.4   -2.95  -22.11      4.8     0.32     2.46
  true fir      15.00   8.32   102.9    38.9    0.75    2.69     10.4     0.16     0.61
  doug fir      15.00  19.18    56.7   113.7    4.16   24.49      9.9     0.46     3.12
  Totals        15.00  11.09   215.5   144.6    3.15   10.64     32.3     1.07     6.84
 ----------------------------------------------------------------
                        STAND AFTER HARVEST              growth remaining
 ----------------------------------------------------------------
  all pines     15.00  33.93    23.9   150.0    6.30   43.34      0.4     0.02     0.19
  Totals        15.00  33.93    23.9   150.0    6.30   43.34      0.4     0.02     0.19
 ----------------------------------------------------------------
  species          et   dbar     tpa   basar    cvol   bdvol     bagro    cvgro    bdgro
 ----------------------------------------------------------------
```

CACTOS is also designed to allow efficient simulation of alternative prescriptions of a single stand. The generation of a complete yield stream and report for each prescription is accomplished by the save (**sv**) and restore (**rt**) commands. The **sv** command internally saves the stand description, yield summary, and report file as they exist at the time of command execution. Simulation of the first alternative can then be continued. The **rt** command automatically saves the yield summary and report file for the first alternative, and then prompts the user for names for the new yield summary and report file, which are restored to the condition existing when the **sv** command was issued. The stand description is also restored to the saved condition. Simulation of the next alternative can be continued from that point. The actual stand description resulting from the alternative prescription may be saved externally at the user's discretion, by using the external save (**es**) command. The externally saved stand description can be entered at a later time for further simulation by entering the new stand (**ns**) command. In this case, the yield summary and report file start with the externally saved condition as the first entry.

Figure 2 illustrates the simulation of four alternative prescriptions for a single stand. Each prescription deviates from the previous one beginning at several nodes. Stand output is saved at nodes 2, 3, 5, and 6 with the **es** command.

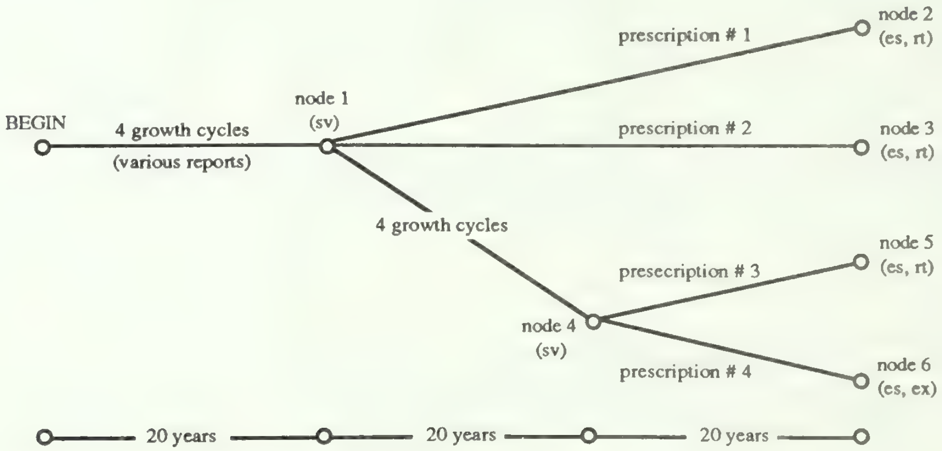

Figure 3. Simulation of four alternative prescriptions of a single stand

The nodes represent points where the **sv**, **rt**, or **es** commands are used. The lines represent other simulation commands issued to grow and thin the stand and to create various reports. Prescriptions 1 and 2 represent two different thinnings occurring after 20 years of growth. Prescriptions 3 and 4 represent two different thinnings occurring after 40 years of growth. Thus, after 60 years of simulation, the user ends up with four stands, each with a different stand history.

Finally, CACTOS allows the simulation of many stands during one entry into the program through the use of the **ns** command. This command allows the entry of a new stand description input file without exiting the program. The previous stand's yield summary and report file are automatically saved, and the user is prompted for the names of the new stand description input file and the two output files. At this point the user is allowed to reenter the initialization routine to set program parameters. The **ns** command reinitializes the program parameters to their default values.

BATCH MODE OPERATION

CACTOS is capable of batch processing multiple stand descriptions through multiple prescriptions. This option is useful for users who wish to run large numbers of plots through the simulator once a set of prescriptions has been decided upon using the interactive mode.

When the user invokes the batch mode, CACTOS prompts the user for two file names, one file contains the "input file names" and the other file contains the "batch commands". The file names file contains the names of the stand descriptions that are to be run through CACTOS. These files may contain any number of individual stand descriptions concatenated together. The commands file contains the keyboard input to cactos for each prescription. There may be any number of prescriptions in the commands file.

After these two input files are successfully opened, the program asks the user to choose the output files to be produced by the simulation. In addition to the yield summary and report file produced in interactive mode, batch mode can produce a "tree list" file. This file is a direct access, unformatted (binary) file designed for post-processing. The user has the option of producing any combination of these output files, by entering "y" or "n" in response to the prompt for each file type. These output files are automatically named by the simulator using the stand description file name and the prescription code. Concatenated input files will produce concatenated output files. As the simulation proceeds, the file name of the input file being processed is printed to the screen.

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PLATIPUS PHYSIOLOGY: DESIGN OF A PLANTATION GROWTH AND CONVERSION SIMULATOR INCORPORATING SILVICULTURE AND WOOD QUALITY

Jerome K. Vanclay[1]

ABSTRACT. A **PLA**ntation **TI**mber **P**roduction and **U**tilization **S**ystem (PLATIPUS) is currently being developed for Queensland's three major plantation species. The growth model will predict not only the volume of timber produced, but also the nature, location and size of defects. It will simulate the effect of silvicultural options such as site preparation, fertilizing, weed control, pruning, thinning and fire. The conversion model will initially comprise submodels for bucking, sawing and grading, but will ultimately also predict veneer, chip, bark and waste outturn. Thus PLATIPUS will allow objective appraisal of the impact of any silvicultural option on both the volume and value of the processed timber in the market place. The paper describes the design criteria, the structure of the system, and discusses the functional relationships required.

INTRODUCTION

Increasing demands on finite plantation areas are forcing forest managers to adopt intensive silviculture to boost plantation yields and wood values. Such management is expensive, and is viable only where returns can be demonstrated. Successful management of plantations involves doing simple operations well, and at the right time (Kirkland, 1985). Although these operations themselves are simple, the best way to achieve a particular objective is seldom intuitive. All operations from site preparation to clearfelling interact, and may influence wood characteristics. Evaluation of commercial gains likely to accrue from any silvicultural option requires an understanding of how processing and marketing opportunities are affected.

Many foresters are blasé about wood quality considerations, assuming that if trees are big and straight, industry will find a way to utilize them, regardless of the size of the juvenile core, or other defects. Industry may well utilize the wood, but the price offered may not be profitable for the grower. There is no doubt that wood quality affects market values. In Queensland, plantation hoop pine (*Araucaria cunninghamii*) which has a relatively uniform density profile, commands a substantial premium over slash pine (*Pinus elliottii* var. *elliottii*). Wood properties are strongly influenced by environment and silviculture, and can thus be enhanced by activities (e.g. pruning) other than those directed at increasing volume increment (e.g. fertilizing).

The Queensland Department of Forestry has always sought to provide high quality timber from its plantations. Until recently, pruning to six metres was prescribed to provide logs suitable for defect-free veneers. However, because of changes in the panelling market, much of this resource is now sawn to premium structural timber. The processing strategy of at least one mill in Australia departs from "conventional wisdom" by sawing large clear logs and peeling small knotty logs to achieve more efficient processing. We can be confident that changes in technology and market opportunities will continue to frustrate planners in their efforts to occupy a niche in the market. However, appropriate simulation models may assist foresters to manage plantations to provide trees of high value with many possible end uses.

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Hence growth models for intensively managed plantations need to do more than just predict average yields — they should predict the effect of intensive silviculture on both the quantity and quality of timber produced. PLATIPUS (an acronym for PLAntation TImber Production and Utilization System) is a proposed computer system which will:

- simulate the growth of a stand under a wide range of environmental and silvicultural conditions, enabling analyses of forest management options;
- simulate the effects of most silvicultural options (site preparation, spacing, fertilizing, weed control, pruning, thinning and fire) on growth and on wood characteristics;
- simulate the conversion of trees and logs into various products (veneer, sawnwood, chips, pulp, etc.) and determine their intrinsic value.

In short, it will provide an efficient mechanism for collating and summarizing research results and making these widely available in a functional form.

SCOPE OF THE MODEL

The Queensland Department of Forestry plantations comprise three major species (43 000 ha of *Araucaria cunninghamii*, 36 000 ha of *Pinus caribaea* var. *hondurensis* and 67 000 ha of *P. elliottii* var. *elliottii*), and PLATIPUS should accommodate all of these.

The philosophy and methodology of growth and yield modelling is well established, but the inclusion of silviculture, conversion simulation and quality prediction introduces additional and demanding requirements. PLATIPUS cannot model every aspect of wood structure, but must concentrate on the key aspects — those which determine the utility of timber in the marketplace. Basic density is the most important within species wood property determining quality for nearly all products (Zobel and Talbert, 1984). Thus, the growth model should provide sufficient information for the density profile, the positions and sizes of knots, and the position of each log within the tree to be reconstructed.

These details can be summarized in two tables. One gives the height above the ground, diameter over bark at the base of the branch (at death for dead branches), orientation, branch angle, and stem radii at branch death and occlusion, for each branch. The other defines, for several ages, the diameter at breast height over bark, total height, height to lowest green whorl, the average density and relative amount of latewood within the current growth ring, and diameters under bark at several specified heights. The tables will not provide details of stem straightness, ovality or pith eccentricity, as these can probably be better handled through predicted population distributions reflecting environment and silviculture. However, these aspects are important, especially in veneer production where compression wood and pith eccentricity greatly affect recovery and quality.

This information will allow the utility and value of processed timber to be determined. Equations are available to reliably determine machine stress grades from density and knot size, and visual grades can be predicted from knot size and position. Density within any annulus can be predicted from age from pith and distance from the lowest green whorl.

CONVERSION SIMULATION

Empirical conversion models (e.g. SILMOD, Whiteside and Sutton, 1983) based on regression equations are effective but inflexible, being restricted to a narrow range of options. To provide the intended scope, PLATIPUS requires the more versatile approach of simulation modelling, which mimics the actual conversion process. It will encompass all aspects of the conversion of logs to timber products, including sawing, peeling, slicing, and chipping, but no attempt will be made to model the sawmill itself, to identify bottlenecks in the plant, or to study sawmill design and layout.

As one of the more complex and important aspects of conversion modelling is sawing, initial development will focus on sawing simulation and its components of cross-cutting, seasoning, grading, etc. The sawing module should:

- Simulate the performance of a range of equipment, including the primary breaking-down of sawlogs and resawing to final products;
- Simulate the range of sawing strategies capable within the physical constraints of the selected equipment;
- Provide descriptions of sawn products and estimates of processing times so that product values and production costs can be determined.

Much of the necessary research has been published. For instance, Singmin (1980) developed a sawing simulator which could accommodate oval stems with bends in two directions, but no internal defects. Adkins *et al.* (1980) studied the predicted occurrence of knots and core defects in simulated sawing, and derived grades from these data. PLATIPUS simply has to combine this work, and link it to a growth model. Conversion could be simulated through geometry and algebra, or a simple approximation could be implemented by representing a log as a three dimensional array of cells (e.g. 1 cm × 1 cm × 10 cm).

GROWTH MODEL

The growth model will, at least initially, be kept relatively simple to hasten development and minimize input data required to use the model. At this stage, we are attempting to quantify the first order effects, without necessarily accounting for all the biological intricacies involved. No attempt will be made to develop a complex nutrient cycling model, but in order to provide the required detail concerning branch size, PLATIPUS will be more complex than most crown models (e.g. Mitchell, 1975). Because of the effect of knots on wood quality and the difficulty in deterministically modelling branches, it is appropriate that PLATIPUS be stochastic.

The model should be amenable to further development. One way to achieve this is to distinguish the basic growth potential from the specific effects of treatment, and to employ separate equations for potential height and volume increments. The effects of silviculture can be incorporated by employing multipliers to these basic equations. Such an approach would be highly modular, and conducive to on-going refinement.

POTENTIAL GROWTH FUNCTIONS

The standard height-age curves used for site index may be utilized, and the height growth of individual trees can be predicted using a modifier function (e.g. Arney, 1985).

A tentative stem volume increment function for *P. elliottii* is:

$$VI = 0.00230\, I^{3.378} A^{0.3817} L^{0.8790} e^{-0.02194BA} \qquad (1)$$

where VI is the total stem volume increment (m^3/ann under bark), I is a simple light index, A is the horizontal projection of crown area (m^2), L is crown length (m) and BA is the stand basal area (m^2/ha). The light index is a simple measure of competition for light, determined as the mean of the cosines of the angles from the effective centre of the crown (computed as the tree height minus 0.24 times the crown length) to tips of the nearest neighbour in each of the four cardinal directions. Thus it represents the relative area of sky "seen" by the subject tree.

An alternative formulation, reflecting the gross photosynthesis minus respiration, was not supported by data currently available. However, equation (1) provides reasonable estimates of increment for a wide range of conditions. Although volume increment may increase monotonically with tree size, it is spread as an increasingly thin veneer over the growing volume of the tree, resulting in realistic diameter increment forecasts (Figure 1).

The potential growth should be adjusted using modifier functions, to account for site and silviculture. Most modifiers will predict the relative increment (usually in the range 0.0 to

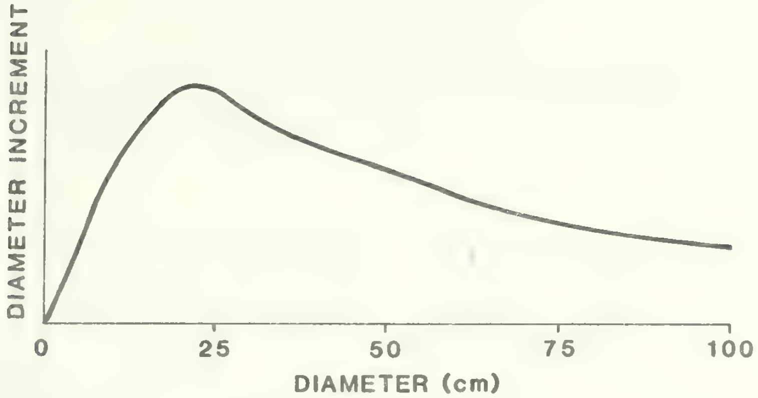

Figure 1. Open-grown Diameter Increment Trend implied in Equation (1)

2.0) as a function of intensity (e.g. amount of fertilizer applied) and time since treatment. Different modifiers may be required for height and volume increments.

MODIFIER FUNCTIONS

PLATIPUS should correctly predict the response to the various activities comprising site preparation: cultivation, ripping and, especially on poorly drained sites, mounding. These activities enhance the ability of a tree to occupy and exploit a greater volume of soil more quickly. Soil bulk density is a simple measure which is both influenced by site preparation and correlated with tree growth, and provides a suitable mechanism for modellling site preparation. Root elongation can be modelled as a function of soil bulk density, and the predicted volume of soil exploited can provide the basis for modifier functions. Provided that the soil bulk density profile is known, PLATIPUS could model the root growth along the row, between the rows, and in depth. This strategy would also enhance the ability of PLATIPUS to forecast windfirmness.

One option for modelling the fertilizer response includes the modelling of soil and foliar nutrient levels. However, measurement of soil nutrient levels is both difficult and imprecise. Although there are also some difficulties in measuring foliar nutrient levels, this approach is virtually the only way to ensure a robust model. It is expedient to predict the change in foliar nutrients over time resulting from a fertilizer application, as a function of fertilizer type, amount and soil type. The predicted change can be added to the underlying foliar nutrient level, and employed to predict the growth multiplier. This would require a characteristic foliar nutrient level to be assigned to each soil type.

For example, the increase in foliar phosphorus after applying phosphate fertilizer to *P. elliottii* can be predicted by (Figure 2):

$$\Delta P = 0.0743\, F_p^{\,0.257t}\, t^{1.35}\, e^{-1.70t} \tag{2}$$

where F_p is the amount of phosphate fertilizer applied ($kg/ha\ P$) and t is the number of years since it was applied. The relative growth rate of *P. caribaea* may be predicted as a function of foliar N and P (Bevege, 1978) (Figure 3):

$$R = 1.09 + 1.48\,N - 0.0617\,\frac{N}{P} - 9.09\,P \tag{3}$$

where R is the relative stem volume increment, and N and P are the foliar concentrations (%) of nitrogen and phosphorus respectively. These equations are based on limited data, and are employed because of their availability rather than their utility. Although they provide reasonable predictions for fertilizer applied at establishment, they are inappropriate

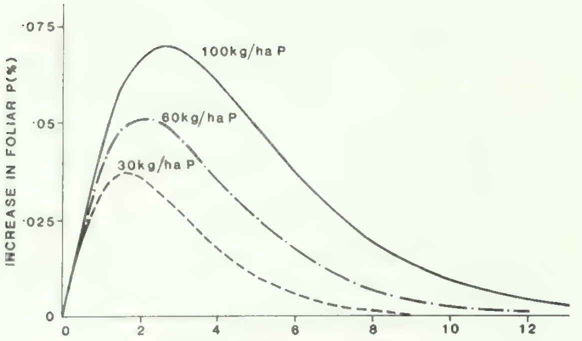

FIGURE 2. INCREASE IN FOLIAR P AFTER PHOSPHATE FERTILIZER

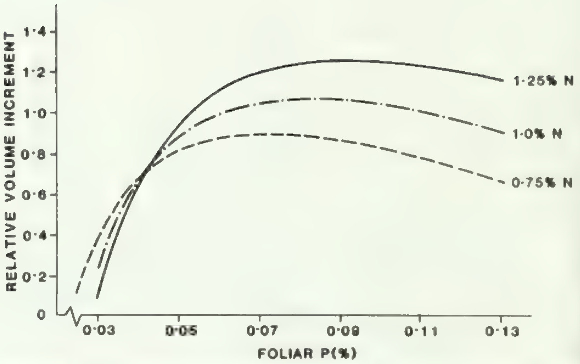

FIGURE 3. EFFECT OF FOLIAR P AND N ON INCREMENT RATE

for fertilizing an older stand. Equations (2) and (3) fail to account for the situation where phosphorus is initially sufficient, but becomes limiting during periods of rapid growth and as the stand biomass increases. A more reliable approach would account for the available nutrients in the soil, the proportion extracted by the crop, and the standing biomass.

Fertilizers may do more than increase the growth rate; they may also influence wood characteristics. Nitrogen in particular, may alter wood density by changing the relative amount of latewood, and may influence foliage development and retention.

Weed control may be modelled by simulating the growth of weeds in three broad groups, grasses, shrubs and trees, each with a characteristic height growth and rate of spread. Weed competition can then be dealt with in the same way as intra-specific competition. As water may be a factor limiting growth, it may be necessary to model water relations, and the uptake of water by weeds. A further complication is the allelopathic effect that some weeds may exert.

The major effects of thinning, pruning and fire are easy to model. Fire kills branches up to the scorch height, pruning removes branches up to the pruned height, and thinning removes the nominated trees.

PARTITIONING VOLUME INCREMENT

The predicted stem volume increment must be partitioned along the stem. Firstly, the conical section at the top of the tree should be elongated to accommodate the predicted height growth. This cone may be based at 10 cm diameter (or the base of the green crown, whichever is higher). If insufficient volume increment is available, the height increment should be reduced until this cone can be achieved. Any remaining volume increment can then be distributed over the bole such that the sectional area increment at any point is proportional to the volume of green crown above it. Trials indicate that this approach produces a realistic stem form.

BRANCH MODELLING

Each branch in the green crown can then be lengthened by an amount determined by the diameter increment at the base of the branch, the relative position of the branch in the tree and the number of branches in the whorl. However, branch elongation stops when it reaches the "zone of influence" of another branch. The new foliage on each branch is determined by the branch elongation, the height to the next branch, and the light index. Branch diameter may be a simple function of branch length. Site and fertilizer appear to affect branching habit, with the more vigourous stands having fewer defects. Branches die a few years after branch growth stops, and a stochastic function simulates the breakage and/or decay of these dead branches. The thinning of an adjacent tree may increase branch breakage.

New whorl initiation occurs at least once each year, when a flush of growth occurs. The number of branches and the branch angle in these whorls are determined by genotype, and branch orientation is random. Single branches can also be initiated during periods of rapid growth, and tend to become ramicorn branches.

OTHER ASPECTS

The simulation interval for many plantation growth models is one year — the model makes annual forecasts, and is invoked repeatedly for projections of more than one year. This resolution is adequate for mature stands, but if PLATIPUS is to provide reasonable predictions of competition from weed growth, a higher resolution is required. Thus PLATIPUS may simulate by months until canopy closure, and then by years.

Many components within PLATIPUS will be stochastic, and the appropriate distributions need to be identified — not all will be normally distributed. A further complication is to ensure the appropriate correlation between the various stochastic components. Hence the variance-covariance matrix needs to be compiled for all stochastic components.

USER INTERFACE

The computational requirements of PLATIPUS should be minimized to enable it to be used interactively on modest computers. Thus it is appropriate to implement it as a plot-based model. The size of the plot should be sufficiently small that processing times are minimal, but large enough to minimize edge effects and any periodicity arising from "wrap-arounds" at the plot edge. A plot containing a maximum of 7 × 7 trees is currently envisaged. This plot could be represented as 70 × 70 pixels of arbitrary size (depending on initial spacing). The exact location of each individual tree will be retained, and trees need not necessarily be centered on a pixel. The ownership and height of occupancy of each pixel is recorded and updated. This simplifies the determination of branch zones of influence, and of light indices.

PLATIPUS should be able to use a wide range of data. Inventory (comprising tree diameters, nominal positions and top height only), research (diameters, heights and actual positions of all trees) and hypothetical data representing stands of any age should be simulated with equal efficacy. As inventory data will provide no details of crown size, equations will be required to predict branch diameters and lengths of both live and dead branches.

As PLATIPUS will be a stochastic model, several runs should be used to give an indication of the most likely outcome, and its variability. It would be helpful for users if PLATIPUS maintained a log of interactions, so that each simulation could be automatically repeated another four times to indicate the median and approximate 66% confidence limits.

DATA SOURCES

The Queensland Department of Forestry has an adequate data base to commence PLATIPUS. Many experiments record annual measurements of tree diameter and height, occasional measurements of lowest live branch and lowest green whorl, and records of tree position and thinning, pruning and other treatments. Some experiments include branch lengths and diameters. These will provide much useful data. Additional information can be gleaned by dissecting trees. The tree, when carefully sawn, reveals much of its history in the form of growth rings, knots and other characteristics (e.g. Somerville, 1985).

BENEFITS

PLATIPUS offers advantages in two areas. In the short term, it will lead to better co-ordination of research effort. In the longer term, it will lead to better plantation management.

PLATIPUS will provide the mechanism and facilities to conduct detailed examinations of the silvicultural options available to any forest stand. It will allow the investigation of the effects of various silvicultural practices on the end product rather than simply on the harvested stem. It facilitates the "fine tuning" of the type, intensity and timing of silvicultural operations such as tending, thinning and pruning. Thus it will enable forest managers to examine their options with greater finesse and have more confidence in their decisions. It will lead to the better co-ordination of forest research, by identifying deficiencies in current knowledge and providing a focus for future research and development work. One of the major benefits of PLATIPUS is that it challenges researchers to express their ideas on tree growth and silviculture in concise and explicit expressions amenable to rigorous testing.

Several other benefits accrue as a result of the conversion simulator. Computer simulated sawing enables the same log to be "sawn" repeatedly using different sawing patterns with strict controls over other factors not possible in sawmill studies. A standard tree can repeatedly be optimally processed, varying the stump height or the small end diameter to realistically appraise the economic utilization limits. It will enable detailed studies of how the quality and value of sawn output (or veneer) is affected by the nature and position of defects within the log, and by log size and form. It will also provide better direction to tree breeding research, by identifying what really constitutes a more useful tree rather than a "better looking tree".

PROGNOSIS

Originally, it was intended that PLATIPUS should be equally useful for investigation on a per hectare basis, as for forest management planning for the entire estate. This is clearly impractical if detailed investigative facilities are to be provided, but PLATIPUS may enable the formulation of a compatible, but more generalized model suited to estate planning.

Initially, PLATIPUS will primarily provide a research tool, providing a focus for research effort and undergoing iterative refinement. The first version may merely approximate the first order effects of silviculture, but it should provide an avenue for understanding, disseminating and co-ordinating research.

One of the questions that PLATIPUS poses relates to the efficacy of site index as a measure of site. Site index is certainly a reasonable summary of past performance once the subject stand has attained the index age, but is it really useful in predicting future growth, especially where management may encompass extremes of silviculture?

ACKNOWLEDGEMENTS

PLATIPUS forms part of the research and development program of the Queensland Department of Forestry, and many officers are thanked for their input. Special thanks are due to Chris Bragg and other members of the PLATIPUS Project Team, and to colleagues in the various Forest Services in Australia and New Zealand.

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A STAND MODEL FOR SIMULATING THE EARLY DEVELOPMENT OF SCOTS PINE CULTURES IN FINLAND

Martti Varmola[1]

ABSTRACT. Models for the development of Scots pine (Pinus sylvestris) cultures are presented. The data consist of 100 temporary plots where 15-year growth is measured. Sites are described with site indexes which are determined by dominant height and 5-year increment of dominant height. Site index estimates are compared with site indexes of forest site types. The base model describes current annual increment of basal area under bark (u.b.). Initial state for growth models is given as basal area u.b, when either dominant height has reached 1.3 m or cleaning has been done. Bark, volume, mean height, and mean diameter models are also derived. Growth tables may be computed for different sites and for different initial number of trees for planted or seeded, cleaned or uncleaned sapling stands with a dominant height of up to 10 m. Models are tested with data from permanent plots of cleaning experiments.

INTRODUCTION

Artificial regeneration has been used in Finland on a large scale since the 1950's. Nowadays the artificially regenerated area is about 140000 ha per year. This equals half of the area regenerated annually. The total area of cultures comprises over 3 mill. ha, which is about 14 % of the forest land in Finland. Scots pine has always been the main species regenerated artificially. Seeding was the main method up to the 1960's, but planting is nowadays used on about 80 % of the area.

Growth and yield models for Scots pine cultures in Finland have been created by Vuokila and Väliaho (1980). These models contain the development of stands from pole stage (dominant height 5 - 8 m) to final cutting. The correspondence between various forest site types (Cajander 1909) and site indexes (H_{100}) is also described.

In most Fennoscandian growth and yield studies (e.g. Eriksson 1976, Hägglund et.al. 1979, Vuokila and Väliaho 1980, Agestam 1985, Ekö 1985) the development of stands before the pole stage is not described. In this paper stand models for the early development of Scots pine cultures up to a dominant height of 10 m are presented. The following stand characteristics are described: basal area both

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over and under bark, basal area median diameter and corresponding tree height, dominant height and volume. A mortality model is not included in the simulation model because of a lack of proper data. Application of models is discussed in relation to models for older stands and with test material.

MATERIAL

The data consist of 100 temporary plots, which cover practically all sites suitable for artificial regeneration of Scots pine in Finland. The geographical distribution is from southernmost Finland (60° N) to above (67° 30'N) the Arctic Circle. The stands have been selected subjectively in order to get as wide a variety as possible in relation to density and site. Of the stands 29 are planted, the rest seeded. In 37 seeded stands cleaning was made 2 to 14 years before measurement.

The plot size varies from 225 to 2000 m^2 so that at least 200 plants are calipered, of which 20 sample trees are selected. Besides the normal tree characteristics height increments (max 15 a), and radial increment at breast height (max 15 a) are measured. At the time of measurement dominant height varied from 3.7 to 10.1 m, age from 12 to 35 years, and density from 1300 to 24000 stems/ha.

The basis for the analysis is the increment data (Table 1), which comprises 819 annual increment periods. In all cases the static variables presented are those in the beginning of corresponding growth period. Volumes contain also trees under 1.3 m high.

TABLE 1. Main stand characteristics of the increment data. G is basal area, V is volume, H_{dom} is dominant height, D_{gM} is basal area median diameter, H_{gM} is corresponding height, I is current annual increment of a variable, and $_{ub}$ is value of a variable under bark.

	Mean	St.Dev.	Minimum	Maximum
I_G, m^2/ha/a	1.1	0.6	0.03	3.3
I_{Gub}, m^2/ha/a	0.9	0.5	0.02	2.6
G, m^2/ha	5.1	4.5	0.0	21.7
G_{ub}, m^2/ha	4.1	3.7	0.0	17.6
I_V, m^3/ha/a	4.0	2.6	0.09	13.2
V, m^3/ha	18.0	17.0	0.3	90.9
I_{Hdom}, m	0.42	0.13	0.03	0.95
H_{dom}, m	4.5	1.7	1.5	9.2
D_{gM}, cm	5.3	2.6	0.2	13.9
H_{gM}, m	3.9	1.5	1.3	8.1

SITE INDEXES

Site index curves based on height and age are usually used in stands with a dominant height of at least 5 to 8 m. In any case the estimate of a site index with such a model is uncertain when dominant height is under 10 m, as is the case in the study material. The use of a site index model for Scots pine cultures (Vuokila and Väliaho 1980) gave on the average values 3 m higher than would have been expected on the basis of a knowledge of forest site types.

Another method is used instead of the height-age model. Hägglund (1976) has developed a model for site classification in young stands ("intercept-method") based on the 5-year growth of dominant height from the height of 2.5 m upwards. For the present study material the model seems to produce logical site indexes. On the average site indexes are equal to indexes of different forest site types, but the deviation in a single forest site type is narrower than when using the dominant height-age model.

In Hägglund's model (1976) the starting point for height growth is fixed, 2.5 m. To be able to estimate the site index with different starting points a height growth model is derived:

$$\ln(Y) = b_1+b_2\ln(X_1+0.01)+b_3\ln(X_2-X_1)+b_4X_2 \qquad (1)$$

where Y is 5-year growth of dominant height (m), X_1 is dominant height before growth period (m), X_2 is site index (H_{100}), and the b_i's are regression coefficients.

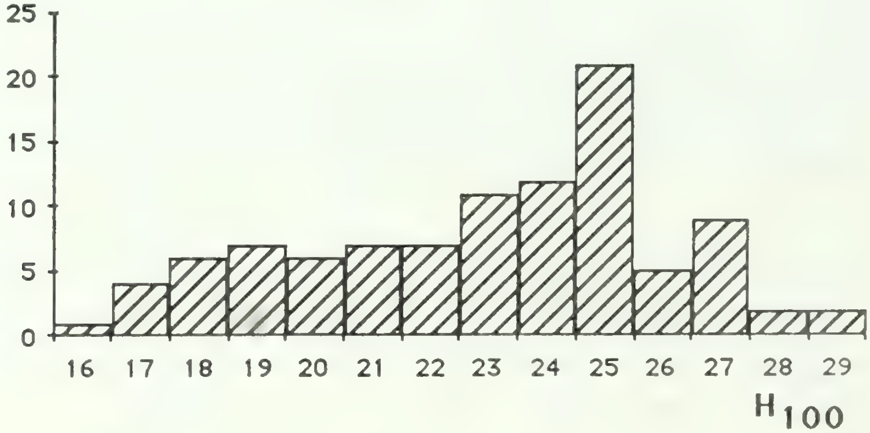

Figure 1. The amount of plots in different site index classes. Site indexes are estimated with the intercept-model (Hägglund 1976) or equation (1).

Annual values can be derived by cubic-spline-interpolation when

5-year points of dominant heights are known. Site indexes are calculated by iteration. Iteration was used in 38 stands, where no value for Hägglund's method was available.

In spite of the difficulties in determining forest site type in a young stand the correspondence between calculated site indexes and those of different forest site types seems rather good. Also the deviation of site indexes, which are determined by Hägglund's model or by equation (1), covers the spread of sites used in artificial regeneration in Finland (Fig. 1).

BASAL AREA GROWTH MODEL

The base model for the simulation system is that of current annual increment of basal area u.b. As in many other studies a multiplicative model is used. The model has the following form:

$$\ln(Y) = b_1+b_2\ln(X_1)+b_3X_1+b_4\ln(X_2)+b_5\ln(X_3)+b_6X_4+b_7X_5 \qquad (2)$$

where Y is the current annual basal area increment u.b. (m^2/ha/a), X_1 is the actual basal area u.b. +0.001 (m^2/ha), X_2 is the site index (H_{100}), X_3 is the number of trees per ha, X_4 is the dominant height at the time of thinning (m), X_5 is a dummy variable (0=planting, 1=sowing), and the b_i's are regression coefficients.

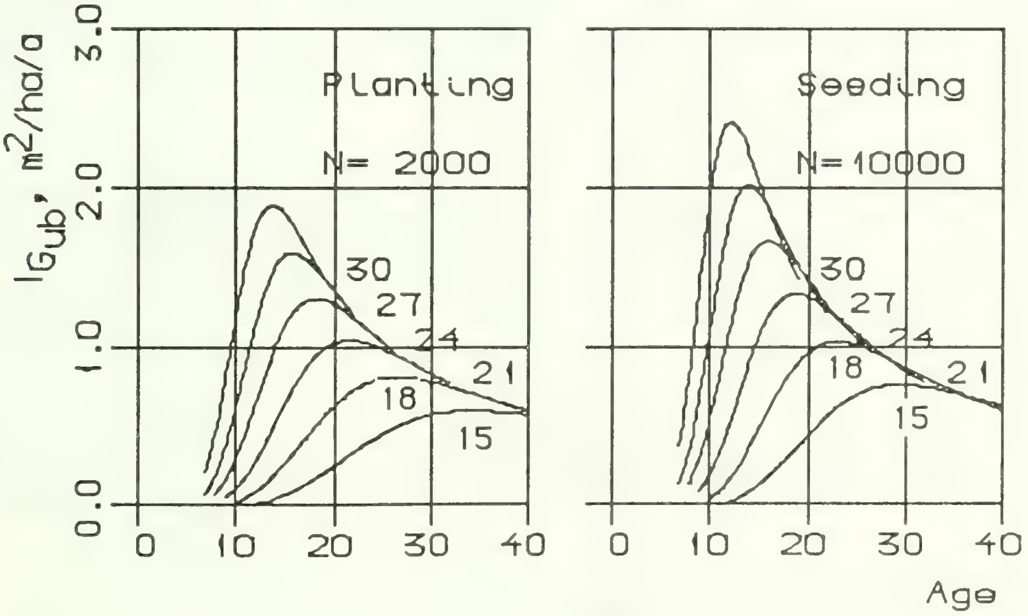

Figure 2. Current annual increment of basal area u.b. (I_{Gub}) in different site classes.

The model is described in two examples (Fig. 2), of which the first represents a typical planted stand and the second a usual density seeded stand without cleaning. The growth curves are limited to a dominant height of 10 m.

In a dense stand growth curves on different sites intersect. This is a sign of overdensity and a need for thinning. A similar pattern has been recognized by Hägglund et. al. (1979) for Lodgepole pine.

OTHER MODELS

In order to get an initial state for basal area two models are derived. The first model describes basal area u.b. when the dominant height has reached 1,3 m, i.e. the breast height age is 1, as a function of dominant height, site index and stem number. In the second model, which gives basal area u.b. after cleaning, site index has no significance as an independent variable. According to other studies site seems to have a negative effect (Elfving and Hägglund 1975), a positive effect (Vuokila and Väliaho 1980) or no effect (Hägglund et.al. 1979) on the basal area after cleaning or thinning. These conflicting results show that models lack some important variables, e.g. density before thinning and type of thinning.

Bark models are derived for converting basal area u.b. to that of o.b. and vice versa. Volume is described by basal area, dominant height, site index, and stem number. Basal area median diameter and corresponding height are modelled, too. Current annual volume increment, which is computed as the difference between annual values, is presented in two examples (Fig. 3).

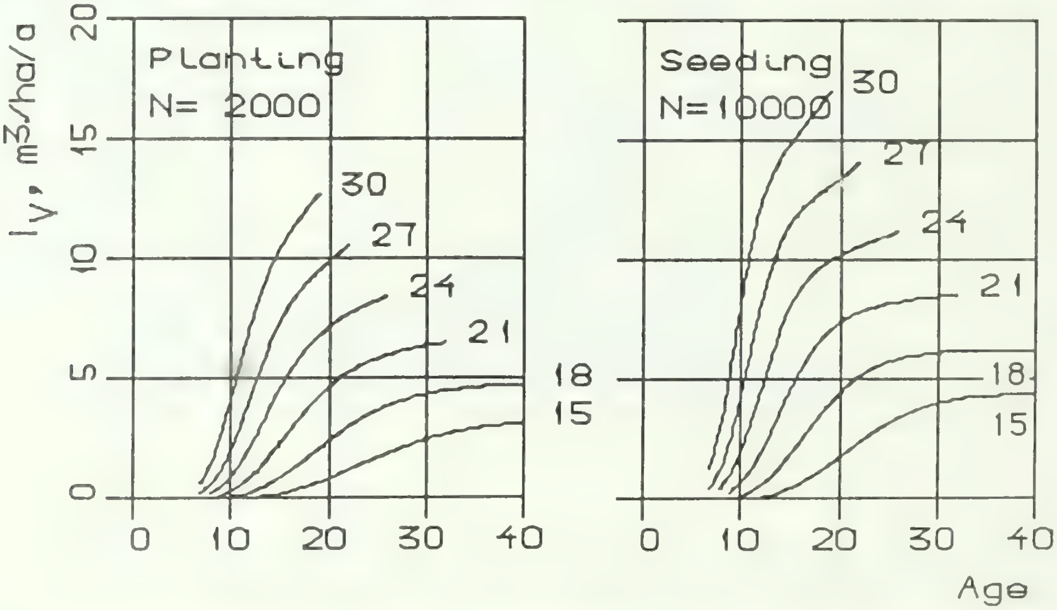

Figure 3. Current annual volume increment (I_V) in different site classes.

Particularly in a dense, uncleaned stand the current annual volume increment curve has a clear turning point when dominant height is about 7 m. This equals the culmination point of the current annual increment of both basal area and dominant height.

APPLICATION OF THE MODEL

COMPARISON WITH OTHER MODELS

In Finland growth and yield of Scots pine cultures is desribed by Vuokila and Väliaho's models (1980) from the pole stage onward (dominant height 5-8 m). The upper limit of models in this study is 10 m of dominant height or 40 years of age. Thus a comparison between both models can be done for their commom area.

According to this study dominant height reaches breast height on the average two years earlier than in Vuokila and Väliaho (1980). This can be seen as a more rapid development of dominant height up to 10 m. The difference between the two studies in site indexes is about one class (3 m).

The same phenomenon can be seen in volume growth. While the development of dominant height is faster in this study, the cumulation of basal area begins earlier, too. Basal area is the main dependent variable in the volume model and thus affects volume growth srongly. The difference in volume growth between two studies is, however, smaller than that in dominant height.

TEST MATERIAL

Fifteen cleaning experiments with 162 plots are used as test material. Density after cleaning varies from 600 to uncleaned with over 10000 trees/ha. Measurements were repeated 4 to 7 years after cleaning. In four stands (49 plots) a third measurement was made in connection with the first commercial thinning at the dominant height of over 12 m.

The correlation between forest site types and site indexes is in all cases strong. The actual development of dominant height follows exactly that of dominant height growth model. In four stands, where development is followed up to 12 m, the largest differences in H_{100} values are only 1 m.

Basal area after cleaning is on the average 17 % (0.6 m^2/ha) smaller compared with measured values. This bias is due to the denser spacing before cleaning in the study material as compared with the test material.

Six years after cleaning the predicted basal area is on the average

7.9 % (0.6 m^2/ha) smaller than measured. The basal area growth model thus underestimates growth. Part of this bias can be due to the model itself. It is obvious that the effect of cleaning has been described unsatisfactorily in the model.

Most of the difference is due to the extraordinary favourable growing period in the test material (growth index 115). In the study material no corrections in radial or basal area increments are made using growth indexes because growth indexes are usually calculated on the basis of old trees and in young trees the effect of climate ought to be smallest (Mikola 1950).

The volume model gives volumes which are on the average 0.4 % (2.8 m^3/ha) too small when compared with the actual values. This is mainly due to the taller stands in the test material. However, even in the area of the study material considerable underestimation (9 %) occurs when dominant height is over 8 m.

With both the mean height and mean diameter models overestimation appears in the test material (5 and 8 % respectively) when compared with actual values.

GROWTH TABLES

Growth tables are of interest for example to a forest manager who wants to estimate the state of a cultivated Scots pine stand and it's development. The following initial values are required: site index, number of trees and, in seeded stands, time of cleaning. Number of trees can vary from 500 to 20000 stems/ha, site index from 15 to 30, and the time of cleaning from 1.5 to 8.0 m of dominant height.

CONCLUSIONS

In young stands the method of estimating the site index with 5-year growth of dominant height is considered to be a sufficient one. With a dominant height growth model no fixed starting point is needed. However, when the dominant height is under 2 m, estimation will be uncertain.

The simulation system contains the prediction of main stand characteristics excluding mortality. This is partly due to the lack of proper material on either dying of plants or birth of new, naturally regenerating plants. On the other hand, mortality is not obvious after cleaning as the test material shows.

The early development of a stand is an intresting part of the whole rotation. Changes are rapid and many characteristics reach their culmination point of annual increment. The question of how to combine different models which describe the early and later develoment has to be solved before different models for the whole rotation time can be used. One possibility is to use cubic-spline- interpolation (see

Borders et.al. 1984)

In this study the development of the most important stand characteristics is described. The study material gives the opportunity to model also the growth of single trees and diameter and height distributions as well.

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USE OF TAPER CURVE IN DETERMINING TREE BRANCHINESS AND PREPARING INSTRUCTIONS ON STAND DENSITIES

Jouko Laasasenaho[1]

ABSTRACT. Taper curve can be estimated when the height and a diameter of the stem at any height are known. Based on the strong correlation between stem taper and branchiness taper curve can be used for computing the quantity of the cross-section area of the branches per unit of stem volume.

Taper curve can also be used for estimating the area of the cambium layer, where stem growth takes place. The sum of the bole surface areas per hectare can be computed for a stand by means of breast height diameter distribution and height curves.

The volume increment of an even-aged stand reaches its maximum about the time of canopy closure. The site index of a stand is a good indicator of its growth capacity. A rich site produces a fairly thick layer of wood on a small bole surface area, but the trees grow branchy and are of poor quality. When the bole surface area is larger, the wood layer is thinner and the quality of the crop is higher. A management regime for a stand may be theoretically based on the bole surface area of a stand in the phase of maximum volume increment.

TAPER CURVE MODELS

Taper curve is calculated in Finland by means of the following polynomial function describing stem form (see Laasasenaho 1982):

$$(1)\quad \frac{d_l}{d_{.2h}} = b1x + b2x^2 + b3x^3 + b4x^5 + b5x^8 + b6x^{13} + b7x^{21} + b8x^{34}$$

where d_l = the diameter at a height of l from the ground

$d_{.2h}$ = the basic diameter at 20 per cent height

$x = 1 - \frac{l}{h}$,the relative distance from the top

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A taper curve can be computed for a stem when diameter at any height and the total height are known. The general model (1) can be rectified by correcting the factors b1, b2, b3 by different methods depending on the tree characteristics measured.

The standard errors of the volume estimates derived with the taper curve models, when the stump heights were the real ones, are shown in percentage below for the three main Finnish species. The dimensions measured were breast height diameter (d) and total height (h), or breast height diameter, upper diameter at the height of 6 m (d6) and total height.

Dimensions measured	Scots pine		Spruce		Birch	
	std. error, % in stem volume					
	a	b	a	b	a	b
d,h	7.7	7.3	8.7	7.5	9.9	8.8
d, d6, h		3.5		3.4		5.0

a) General solution
b) Specific to tree size

The taper curve models clearly are more accurate in the middle and upper parts of the stem if the upper diameter has been measured. If the taper curve is computed with the general equation (1) by tree species, the residual MSEs of stem volume estimates exceed those of the corrected taper curve only by 0.4 percentage units for Scots pine, 1.2 percentage units for spruce and 1.1 percentage units for silver birch. Thus the form of the stems does not vary significantly with size. The standard deviations of the stem diameter estimates derived with the taper curve model at relative stem heights are shown in Fig. 1. The characteristics measured are d.b.h. and height.

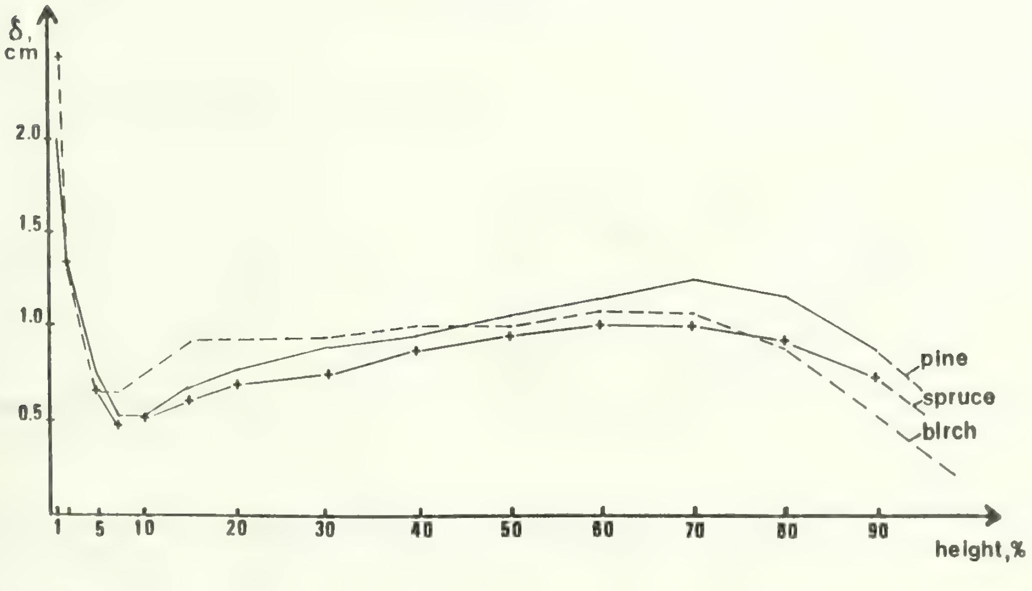

Fig.1. The standard deviations (δ, cm) of the diameter estimates at relative stem heights derived from the taper curve model, when the breast height diameter and total height are known.

BRANCHINESS

The growth of a tree depends on the crown size, i.e. the quantity of needles. It has been shown that a certain amount of needles or leaves requires a certain stem basal area at the crown limit (see e.g. Waring et al. 1982). On the other hand, a given site type can only produce a limited amount of needles or leaves. The more trees there area in a stand, the less does a single tree grow after canopy closure and the start of self-pruning.

When working out taper curve models, the author discovered a clear relationship between the cross sectional area (basal area) of the stem and the cumulative cross sectional area of branches. This relationship from top down to crown limit in some stems is shown in Fig. 2 (see also Laasasenaho 1982). Hari et al. (1986) approached this phenomenon using the water transport systems -hypothesis. In their analysis of 20 pine sample trees, they too, found strong correlations at the crown limit.

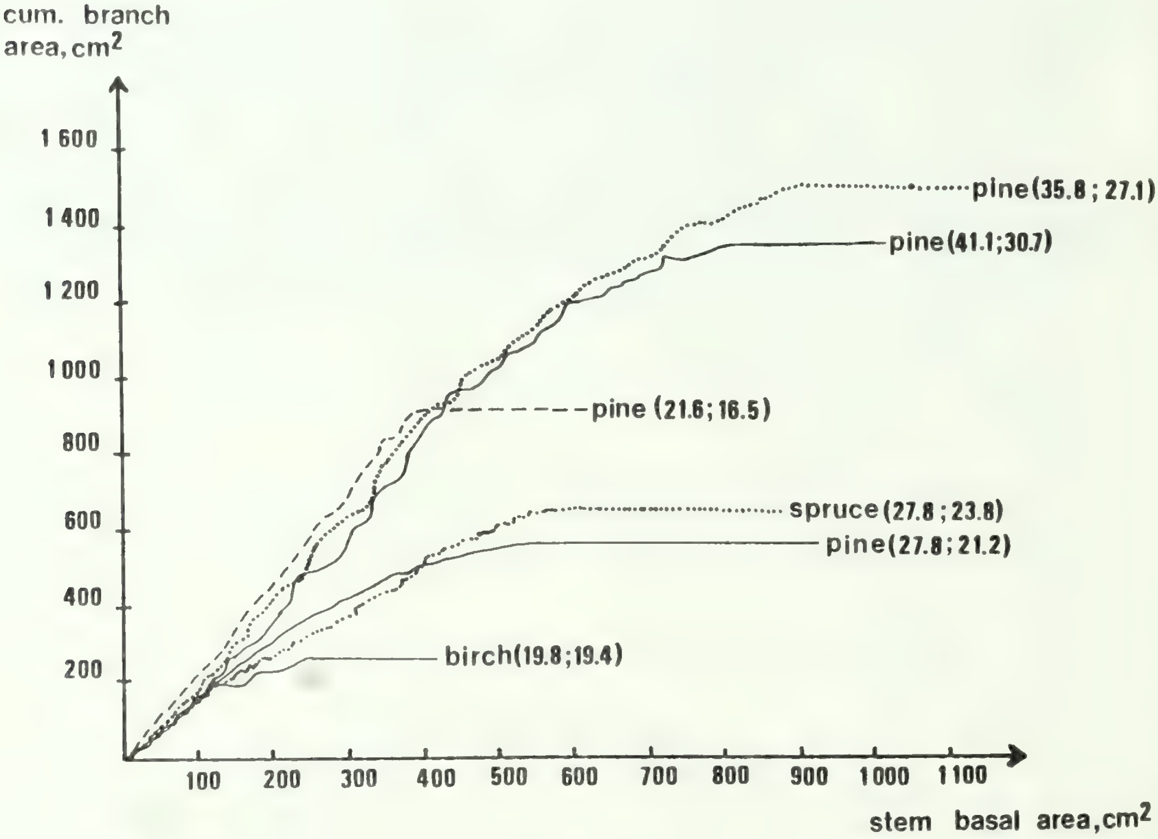

Fig. 2. The dependence between the cumulative cross sectional area of branches (over bark) and stem basal area (over bark) from top down to crown limit in some sample trees. The diameter at breast height and total height are in parenthesis (cm; m).

In the lower parts of coniferous stems where branch deaths and/or self-pruning have occurred, changes in stem basal area probably are strongly related to the amount of heartwood. Changes in stem basal area most likely correlate with branchiness in these lower parts of stems, too, but there are no studies on that available.

The total cross sectional area of branches in the green crown can be computed with the taper curve model if the height of the crown limit is known. Thus, branchiness as the cross sectional area of branches per unit volume of stem can be obtained using the taper curve model. This kind of a branchiness factor could be employed as a work difficulty factor in logging work. At the moment branchiness is estimated ocularly for these purposes in Finland.

There may also be correlations between branchiness and form factors. These, however, need to be studied further to discover e.g. how changes in form factors correlate with branchiness in each diameter class. Dead branches, too, are an important object of study as they affect the timber quality. In addition to these, the estimation of branch mass requires further research. This kind of more specific knowledge about branchiness would be useful for various purposes.

STAND DENSITY AND THE QUALITY OF THE CROP

The canopy size and thus the branch size can be regulated by changing the stand density; the sparser a stand is established, the branchier the trees grow because of the delayed canopy closure and self-pruning. The volume increment of even-aged stands reaches its maximum after the canopy closure. The stand density at the stage of maximum volume increment is essential to the timber quality; in Finland, pine plantation forests reach this stage at the age of 25-40 years. At that stage also the amount of needles or leaves (kg or m2/area unit) is at its maximum. Obviously, the stem basal area at crown limit per area unit, too, reaches its maximum at the same time. The total of bole surface areas of the stems has not, however, grown to its maximum yet, and the diameter increases rapidly all over the stems.

A clear correlation has been found between branchiness and diameter increment of a stem. According to some Finnish studies, the quality of the butt log in a pine stand decreases significantly if, at the butt within the radius of 6 cm from the core, the width of annual rings exceeds 2 mm.

At the time of the canopy closure, the increment mainly takes place in the stem and the branches, as the roots have already grown to meet the requirements of the needle or leave mass. The stem basal area at the green crown limit should not grow too large compared to the bole surface area. Instead, the stems ought to be slender and the lower branches should start to self-prune early.

The stems and the upper branches grow vigorously as the stand reaches the height of a saw log (5-6 m).The richer the site type, the bigger the branches grow. In young forests, the diameter of green branches at the crown limit correlates strongly with the stem diameter at the same height. This varies, however, with the genotype. The stand density clearly has an effect on the length of the green crown and,thus, on the size of the biggest branches (see Persson 1977). The closure stage of the canopy mainly depends on the stand density (stems/area unit), but also on site type: on good sites a stand closes up younger than on poor sites. On good sites branches, too, grow fast. As the quality of a stem is largely determined by the branchiness of the butt log, the establishment density should be high enough to lead to self-pruning before the branches grow too large. The quality improvement to be gained by pruning is the greater, the more slender the branches are.

APPLICATIONS: STAND MANAGEMENT REGIME BASED ON TAPER CURVE MODELS

Taper curve can also be employed in computing the bole surface area, i.e. the area of cambium layer where the actual growth takes place. The total of bole surface areas per area unit can be then computed with the stem diameter distribution and the relevant height curve.

The site index determines the growth potential of a fully stocked stand. By means of the site index, it is theoretically possible to determine a bole surface area for a stand that would keep the width of annual rings below 2 mm. This, however, is quite complicated as the radius increment varies with height. The actual stem volume increment (iv) cannot be accurately calculated from the bole surface area (va) and radius increment at breast height (ir), as seen in Fig. 3. The dependent variable $y = iv/(ir*va)$ has been computed for the stems in a large, carefully measured sample of pines (see Vuokila 1965). The sample trees had been measured from naturally regenerated stands. Evidently, the factor iv/(ir*va) does not significantly depend on stem size. The mean of variable y was 1.21. For the equation $y = 1.5216 - 0.01745 * d$, the coefficient of determination (R2) was 0.152 and the coefficient of variation 27.4 %.

The bole surface area of stems might build a theoretical base for the stand management regime. Some observations have been made which indicate an obvious relation between stand increment and bole surface area within a certain site index (Laasasenaho 1978). The bole surface area should be kept at a certain level in growing stands (see e.g. Lexen 1943, Wilson 1951). The growth level is determined by the site index and, thus, the bole surface area could be computed so that too wide annual rings were avoided. The bole surface areas can easily be converted to optimal basal areas of stands at different height stages when the stem diameter distribution and the height curve are known.

When determining the optimal stand density with simulation models also the quality of the crops has to be considered: the quality distribution of the sawn timber from the logs can be computed as a function of radius increment.

By means of taper curve models, it is also possible to draw up management regimes aiming at a stand basal area at crown limit that is optimal for that site. This, however, requires further studies on correlations between stand density and crown length and branchiness, and also development of more advanced models.

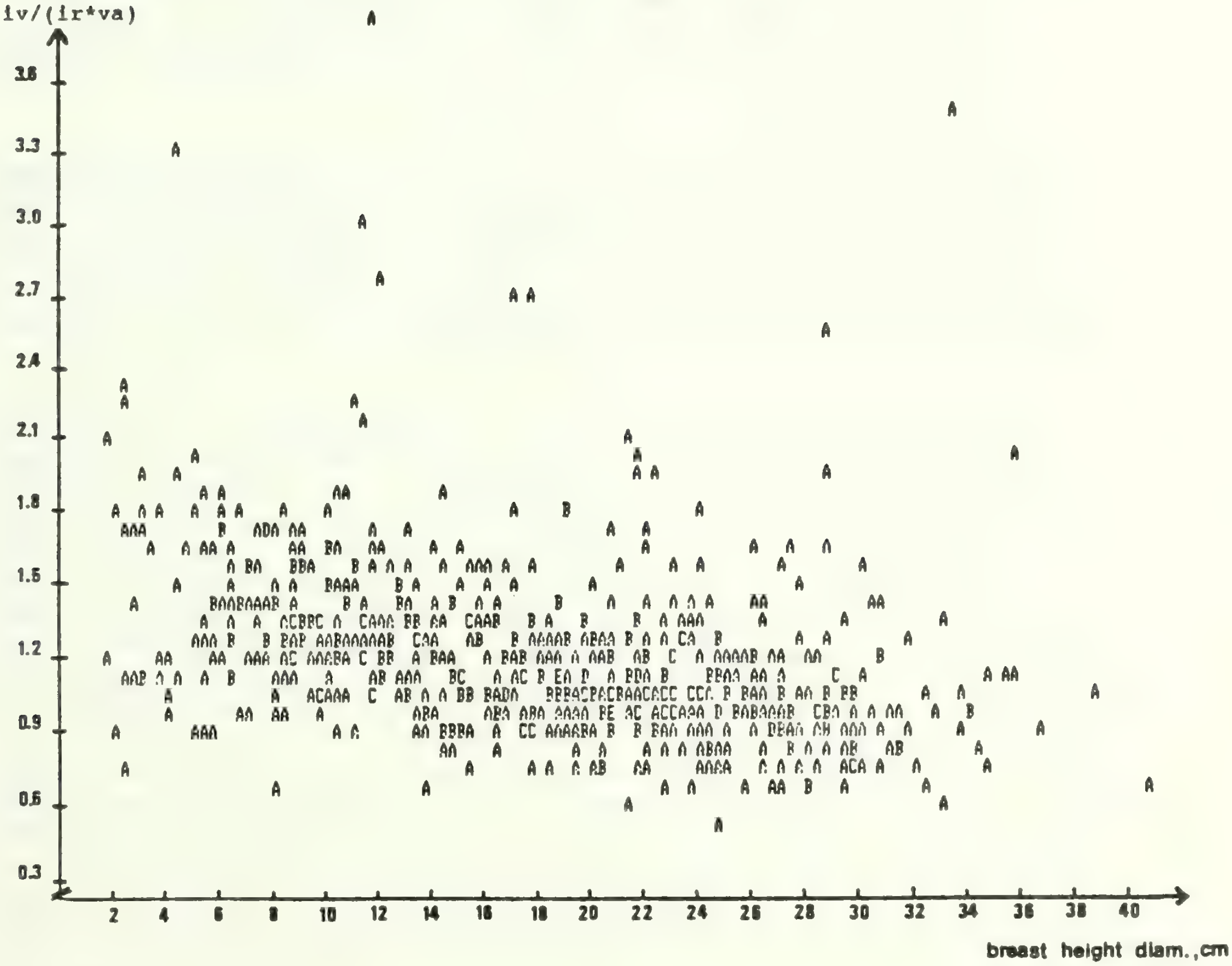

Fig. 3. The dependence of factor iv/(ir*va) on breast height diameter, based on 657 pine sample trees.

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A METHOD FOR PROJECTING STEM QUALITY AND LOG GRADE DISTRIBUTION IN SUGAR MAPLE

Gary W. Lyon and David D. Reed[1]

ABSTRACT. A method is presented for incorporating changes in butt log grade and distribution of gross board foot volume by log grade over time into an existing stand table projection system for sugar maple. Using a set of linear discriminant functions future tree grade distribution is predicted. Then further linear discriminant functions are applied to estimate the proportion of volume by log grade in each tree grade. The end result is a projection of volume for each log grade.

INTRODUCTION

There is a great deal of interest in managing hardwood sawtimber stands with a selection harvesting system the North Central Region. Purportedly, a selection system, if used properly, can improve sawtimber quality in the stand over time by selecting against trees which have poor form or lack vigor. Eventually, as the poorer quality trees are removed, overall timber quality improves and growth increment per acre increases.

Guidelines for marking selection harvests and projection models to predict future stand structures and estimate timber volume are available (see Arbogast, 1957, Adams and Ek, 1974 among others). Yet, neither these guidelines nor these projection models estimate how the timber quality in a stand changes over time, nor do existing stand projection models predict timber grade recovery from harvesting. Without some idea of what products a forest manager can expect to obtain from harvesting under alternative management regimes, financial analysis to determine a preferable management regime for a given set strategic objectives is difficult.

This paper presents a method of using discriminant analysis to 1) predict future stem quality (sawlog grade of the butt log) from existing stand inventory data and 2) estimate the gross Scribner board foot scale volume, by log grade, from current and predicted future saw timber inventories. Stem quality equations are presented for four species: sugar maple (Acer saccharum), red maple (A. rubrum), yellow birch (Betula alleghaniensis) and basswood (Tilia americana). Due to the species composition of stands studied here, only equations for estimating volume by log grade are given for sugar maple. Finally, these equations are incorporated into an existing stand projection model, SHAF (Adams and Ek, 1974), to estimate stem quality distribution

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by diameter size class and volume by log grade.

DATA SOURCE

Data for this study are individual tree measurements from one-fifth acre permanent plots located on the Ford Forestry Center, Michigan Technological University in Baraga County, Michigan. Plots, initially established and measured in the 1950's, have been remeasured every five years. Stands in which these plots are located were predominantly sugar maple, which represented at least 50 percent of the total basal area in the stand, with red maple, yellow birch, basswood, elm (*Ulmus americana*), and hemlock (*Tsuga canadensis*) also present. Since the plots were established, these stands have been managed under an individual tree selection system on a 10-year cutting cycle. Trees removed during harvesting were bucked to obtain the best log grade distribution. Each log was graded according to standards set by the Northern Hardwood and Pine Manufacturer's Association to grades 1, 2, 3, and non-merchantable. Approximately 800 thousand board feet of sugar maple was harvested and recorded during the study period.

METHODS

Discriminant analysis, used here to develop equations which estimate both the proportion of trees within a diameter size class having butt logs of a specified sawlog grade (tree grade) and the proportion of gross volume in each sawlog grade that can be expected from each tree grade by diameter size class, has been used in a wide variety of fields, including medicine and the social sciences, to interpret or study ways in which groups differ and to classify cases into groups that they most resemble. Groups used in this analysis are tree grade and log grade which satisfy the condition of mutual exclusivity. Data cases are described by characteristics such as basal area per acre, diameter, etc. Those characteristics that help identify to which group each data case belongs are discriminating variables. The process of deriving equations for the purpose of classifying additional cases into groups is accomplished by developing discriminant functions which combine the discriminating variables in a manner that allows one to distinguish which group a case most closely resembles.

Viability of using discriminant analysis depends upon not violating the several assumptions behind deriving the solution technique for estimating coefficients in the discriminant functions. These assumptions include: 1) no discriminating variable may be a linear combination of other discriminating variables, eliminating redundant variables, 2) population covariance matrices must be equal for each group, simplifying the process of coefficient estimation, and 3) each group must be drawn from a population which has a multivariate normal population, permitting tests of significance and estimation of probabilities for group membership.

Only four species present in the plots, sugar maple, red maple, yellow birch and basswood, had enough data cases to be included in the stem quality analysis. Table 1 summarizes the initial/final tree grade transition matrix for sugar maple, indicating the number of trees that after a five-year period either maintained the same tree grade or changed tree grade. Tree grade transitions for the other species are similar. Discriminant functions estimating log grade distribution were developed only for sugar maple due to the relatively small volumes harvested of other species.

Table 1. Number of data cases by initial and final tree grade over a five-year measurement period for sugar maple.

Initial Tree grade	Final Tree Grade 1	2	3	nm[a]	Dead	Total
1	680	8	1	1	0	690
2	138	994	21	0	0	1153
3	0	312	1225	7	4	1544
nm[a]	0	1	6	26	0	33
Dead	0	0	0	0	6	6
Total	818	1315	1253	30	10	3426

[a] The non-merchantable (nm) grade class includes cull trees as well as trees in the 12-inch DBH class that do not have any merchantable sawlog volume.

LINEAR DISCRIMINANT FUNCTIONS

The method for predicting the future tree grade for an individual tree is conceptually similar to that used by Ffolliott and Rasmussen (1983). Tree grade change during a measurement period is expressed as a function of the the discriminating variables, ie. tree and stand characteristics. The relationships between future tree quality and these discriminating variables are expressed as probabilities of a tree falling into each of the four tree grade classes (1, 2, 3, and non-merchantable) given the initial tree grade and discriminating variables. These probabilities must be constrained to sum to unity.

A set of linear discriminant functions, a linear combination of discriminating variables, was developed to assign a tree to a future grade class; one function for each possible class for each of the four tree species analyzed. The linear discriminant functions

$$f_i = b_{0i} + b_{1i}X_1 + b_{2i}X_2 + \dots + b_{ki}X_k \qquad (1)$$

where f_i is the function associated with the ith class, $X_1, X_2, \dots, X_k$ are the discriminating variables and $b_{0i}, b_{1i}, \dots, b_{ki}$ are coefficients to be estimated, were combined as

$$P_i = \frac{\mathrm{EXP}(f_i)}{\sum_j \mathrm{EXP}(f_j)} \quad j=1,..,n \qquad (2)$$

where n is the number of tree grade classes, to estimate the probability, P_i, of the tree falling into the ith grade class. Once the appropriate discriminating variables were selected and the coefficients were estimated, the probabilities could be used to calculate the expected future tree grades.

RESULTS

TREE GRADE PROJECTION

The sets of linear discriminant functions to estimate future tree grade for each of the four species are found in Table 2.

Table 2. Linear discriminant functions to predict tree grade distribution for the four species.

Species	Equation[a]
Sugar Maple	
f_1	$= 2.83482D + 0.27235H + 0.11994B + 20.02377Q_i - 50.60788$
f_2	$= 2.82284D + 0.27972H + 0.12747B + 28.76861Q_i - 65.86915$
f_3	$= 2.96217D + 0.22466H + 0.13210B + 35.09009Q_i - 83.45056$
f_4	$= 3.87285D + 0.16780H + 0.15222B + 43.83247Q_i - 131.49264$
Red Maple	
f_1	$= 5.07973D + 0.17642N + 35.44741Q_i - 85.92308$
f_2	$= 5.23850D + 0.15744N + 57.28349Q_i - 119.88573$
f_3	$= 5.21592D + 0.15576N + 72.28424Q_i - 157.71202$
f_4	$= 6.69626D + 0.17713N + 95.81834Q_i - 267.74310$
Yellow Birch	
f_1	$= 2.74359D + 19.25625Q_i - 36.42369$
f_2	$= 2.71074D + 31.16073Q_i - 54.67333$
f_3	$= 2.68454D + 41.70047Q_i - 81.29487$
f_4	$= 3.72306D + 56.30064Q_i - 151.00362$
Basswood	
f_1	$= 1.40133D + 0.67861H + 14.47794Q_i + 0.60460DP - 63.00177$
f_2	$= 1.03584D + 0.62429H + 22.04653Q_i + 0.54062DP - 62.57648$
f_3	$= 1.31015D + 0.52681H + 27.36351Q_i + 0.40901DP - 69.02361$
f_4	$= 2.33171D + 0.92095H + 39.20051Q_i + 0.47094DP - 44.90158$

[a] Notation: D = d.b.h (inches); H = merchantable height (feet to a 10-inch top); Q_i = initial tree quality (1=Grade 1, 2=Grade 2,3 =Grade 3, 4=Non-merchantable); N = number of trees per acre; B = basal area per acre ($ft.^2$/ac.); DP = diameter percentile (among trees larger than 5.1 in. dbh.).

As a test of the ability to project tree grade for individual trees, projected future tree grade was assigned to each tree, or data case, by selecting the tree grade with the highest computed probability of occurrence. Thus, some trees were assigned the same grade as they had initially whereas others were assigned higher or lower grades. The equations for sugar maple classified future tree grades correctly 85.7 percent of the validation set, and red maple, yellow birch and basswood had 93.7, 91.1 and 85.2 correct classifications respectively. As an additional test approximately twenty percent of the data cases, selected randomly, were set aside initially for validation. Correct classifications on this validation set were 85.7, 93.7, 91.1 and 84.5 percent for sugar maple, red maple, yellow birch and basswood respectively.

INITIAL TREE GRADE

Model formulation for the initial grade distribution is the same as that described in Equations 1 and 2 above. Linear discriminant functions listed in Table 3 are used in Equation 2 to estimate the probability of a tree being a particular grade.

Table 3. Linear discriminant functions to predict initial tree grade distribution for the four species.

Species/ Tree Grade	Equation[a]
Sugar Maple	
f_1	0.71781D +0.17038H +0.21367B -0.03755N +0.58992DP -46.22631
f_2	0.37544D +0.12978H +0.21388B -0.03415N +0.59429DP -39.25904
f_3	0.29791D +0.01426H +0.20090B -0.07533N +0.55311DP -31.47001
f_4	1.13173D +0.12035H +0.20015B -0.01389N +0.48020DP -41.01268
Red Maple	
f_1	4.61047D - 0.08594H + 0.16944N - 59.81389
f_2	4.41336D - 0.16648H + 0.15272N - 49.34744
f_3	3.80912D - 0.23000H + 0.14345N - 36.32275
f_4	5.01169D - 0.39405H + 0.16371N - 56.05691
Yellow Birch	
f_1	2.09673D + 0.37670H - 25.87860
f_2	1.81147D + 0.32757H - 19.48805
f_3	1.56718D + 0.23194H - 13.92268
f_4	2.21918D + 0.26432H - 27.17149
Basswood	
f_1	2.06211D + 0.44728H - 29.93459
f_2	1.46557D + 0.36634H - 17.11802
f_3	1.41478D + 0.16080H - 11.38761
f_4	2.30109D + 0.39691H - 35.08628

[a] Notation: D = d.b.h (inches); H = merchantable height (feet to a 10-inch top); N = number of trees per acre; B = basal area per acre (ft.^{2}/ac.); DP = diameter percentile (among trees larger than 5.1 in. dbh.).

The ability to project future tree grade using the discriminant functions listed in Table 2 depends upon the availability of initial tree grades. Since initial tree grade information is frequently not available, this second set of discriminant functions were developed to classify trees into initial tree grade classes. This permits the use of the tree grade projection model presented above, but should not be used in place of actual tree grade information where it is available.

As with the grade projection equations, the initial grade classification equations were tested on both the data cases used to develop the equations and on a validation set containing approximately 20% of data cases chosen randomly. On the development data cases the equations correctly classified 61.1, 73.0, 58.9 and 71.8 percent of the data cases for sugar maple, red maple, yellow birch and basswood respectively. For the validation set correct classifications were obtained for 60.8, 70.9, 58.1 and 69.7 percent of the data cases (same order as above). These initial grade classification functions should only be used when initial grade information is not available.

PREDICTING LOG GRADE DISTRIBUTION

Linear discriminant functions for log grade grade distribution, having the form expressed equation 1, are listed in Table 4.

Table 4. Linear discriminant functions for estimating the proportion of gross scale Scribner board foot volume by log grade and tree grade for sugar maple.

Tree Grade	Equation
1	$f_1 = 2.88375D - 0.01794MH - 28.52515$
	$f_2 = 2.78007D - 0.09500MH - 25.47240$
	$f_3 = 2.71707D - 0.01821MH - 26.63229$
	$f_4 = 4.28935D - 0.43834MH - 48.64153$
2	$f_1 = 0.67976MH - 0.00855V - 14.95602$
	$f_2 = 0.62226MH - 0.01271V - 9.68775$
	$f_3 = 0.61606MH - 0.01304V - 10.67902$
	$f_4 = 0.68042MH - 0.01930V - 13.30496$
3	$f_1 = 1.61159D + 0.35985MH - 25.34882$
	$f_2 = 1.56355D + 0.31424MH - 21.01747$
	$f_3 = 1.65759D + 0.21047MH - 17.63129$
	$f_4 = 1.41023D + 0.22881MH - 16.55437$
4	$f_1 = 1.09785TH + 0.05924MH - 0.02645V - 51.62128$
	$f_2 = 1.24829TH + 0.09424MH - 0.03303V - 45.57575$
	$f_3 = 1.24302TH + 0.09487MH - 0.03470V - 43.90818$
	$f_4 = 1.18998TH + 0.05856MH - 0.03316V - 38.54151$

[a] Notation: Grade 4 = non-merchantable, D = d.b.h (inches), MH = merchantable height (feet to a 10-inch top), TH = total tree height (feet), V = total gross scale board foot (Scribner's) volume, fi = discriminant function for the ith log grade (nm indicates non-merchantable due to either size constraints or cull)

These functions can be used in equation 2 to estimate the proportion (P_i) of a tree's volume in each log grade. Groups and data cases for estimating log grade distribution are different from those used in the tree grade analysis. Groups are log grades rather than tree grades. During the estimation process multiple data cases were generated for each tree from available data. Rather than determining the proportion of each tree's volume falling into each log grade for the entire data set, each 25 board feet of log volume by grade was used as a data case for each log grade. For example, if a tree contained 200 board feet with 150 board feet in grade 1 logs and 50 board feet in grade 2 logs, six data cases, each with identical tree variable values, were generated for the grade 1 volume and 2 data cases were generated for the grade 2 volume. This procedure of generating multiple data cases per log effectively weighted the results in favor of high tree volumes, possibly introducing autocorrelation among data cases from any given trees. Data cases between trees were assumed to be independent. This autocorrelation may be a problem in relatively small data sets with few trees.

APPLICATIONS

STAND PROJECTIONS

The set of linear discriminant functions reported here have been incorporated into the SHAF model (Adams and Ek, 1974) to project stand tables which distinguish numbers of trees per acre, basal area per acre and gross tree scale volume per acre by tree grade within each diameter size class (Reed et al.,1985). Furthermore, gross log scale volume is estimated by log grade for each tree grade within each diameter size class on a per acre basis (Reed, et al., 1987). An example from the combined SHAF model and the discriminant functions, named PROQUAL for quality projection, showing tree grade distribution and log grade distribution for one size class in a hypothetical sugar maple stand is presented in Table 5.

The discriminant functions presented here can be incorporated into any tree or stand projection model which endogenously generates values for numbers of trees per acre, basal area per acre, dbh., total and merchantable tree height, and diameter percentile for the tree within the stand (for trees larger than 5.1 in. dbh.).

Two major advantages accrue from incorporating grade into a stand or tree projection system. Improved estimation of future harvest output by product class can aid forest managers who must plan to provide specific outputs to production facilities in an integrated forest products company. Because prices vary widely among different product classes, a projection of the log grade distribution can improve estimation of potential financial returns that are often performed with average log prices. The increased resolution obtained from projecting tree grades and log grade recovery can be used to evaluate the financial viability of a variety of management regimes for selection harvesting in northern hardwood stands.

Table 5. Example of tree grade and log grade distribution from the PROQUAL model for two diameter size classes for sugar maple.

DIAMETER CLASS	TREE GRADE 1	2	3	NON MERCHANTABLE	TOTAL
14					
T/A[a]	0.2	1.33	8.8	2.7	13.0
B/A[b]	0.2	1.43	9.4	2.8	13.9
Volume					
Grade 1[c]	6	2	3	1	12
Grade 2	6	88	47	16	158
Grade 3	4	28	669	53	753
Grade NM	0	4	88	173	266
Total vol.	15	122	807	243	1188

[a] Trees per acre.
[b] Basal area per acre ($ft.^2$).
[c] Scribner board foot volume by log grade (grade NM=non-merchantable).

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PREDICTION OF BRANCH DIAMETER AND BRANCH DISTRIBUTION FOR DOUGLAS-FIR IN SOUTHWESTERN OREGON

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ABSTRACT. Wood quality is an aspect of forest yield that has often been neglected in growth and yield predictions. Branch size and branch distribution are two major determinants of wood quality due to their influence on wood structure and mechanical properties. A methodology was explored to modify an individual-tree, distance-independent growth and yield model (ORGANON) to allow prediction of whorl locations and their corresponding mean maximum branch diameters in Douglas-fir. Simulation results were consistent with past demonstration of larger average branch diameters obtained from stands of greater initial spacing. The described simulation approach facilitated description of log distribution (first two 32-ft logs) by various branch size and whorl frequency indices.

INTRODUCTION

Wood quantity and quality together determine the potential value and utility of a commercial forest stand. Efficient forest management requires the ability to predict effects of varying silvicultural regimes on both aspects of wood yield. Conceptual and statistical techniques presently exist for forecasting wood quantity, hence this dimension is predicted by virtually all forest growth and yield models (e.g., Burkhart et al. 1981, Wycoff et al. 1982). Wood quality, however, is largely ignored in these models and remains virtually unknown for a wide array of silvicultural regimes.

As old-growth inventories diminish in the western U.S. and as more of our wood is procured from managed plantations nationwide, silvicultural technology necessary to continue producing wood of an acceptable quality assumes critical importance. The alarmingly poor quality of wood removed from managed stands has only recently received the attention it deserves (Senft et al. 1985). Regardless, measurement of wood quality has remained elusive due to ignorance of tree structural effects on wood properties, as well as to lack of modelling methodology for predicting those tree characteristics known to, or stongly suspected to, affect wood properties. Access to the former is ensured once wood properties are analyzed relative to their position in the stem and relative to the dynamics of crown morphology. Similarly, innovative methodology for modelling crown parameters in managed stands will provide the necessary links among growing space, crown dynamics, and stemwood structure.

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Numerous interacting components of wood structure ultimately determine the mechanical properties of wood. These components are thought to include fiber length, specific gravity, microfibril angle, and degree of grain distortion, each of which can in turn be influenced by knot size, knot distribution, and physiological age of the wood (juvenile vs. mature wood) (Haygreen and Bowyer 1982). Knot size, for example, has been shown to exert a major influence on machine stress ratings in Douglas-fir lumber (Whiteside et al. 1977). Gross tree or log characteristics relate ultimately to crown development since crown size dictates both branching patterns (James and Revell 1974, Carter et al. 1986) and size of the juvenile wood core (Cown 1974). Therefore, silvicultural treatments that alter crown development of individual trees will have a direct effect on the quality of wood produced. Crown development has been shown to respond strongly both to variations in initial spacing (Stiell 1966, Curtis and Reukema 1970) and to differences in thinning intensity (Briegleb 1952), and in fact, direct effects of spacing on branch size and distribution have been well documented (Grah 1961, Kenk and Unfried 1980). In recognition of these relationships, silvicultural regimes have been proposed with the primary objective of yielding logs of an intended quality, or more specifically, logs with a certain minimum knotty core (Whiteside 1962) or with a minimum branch size (Whiteside et al. 1977).

Most individual-tree growth simulators contain both a height growth model and a crown recession model. For those species whose crowns are dominated by annual whorls of branches, the positions of major branches or knots can be obtained from height growth predictions, and mean maximum branch diameter per whorl can be estimated at time of whorl mortality, as predicted by the crown recession model. The objectives of this paper, therefore, were: 1) to illustrate a methodology for incorporating branch size and branch distribution predictions into ORGANON, an individual-tree, distance-independent growth and yield model; and 2) to explore by subsequent simulation the effects of various silvicultural regimes on these branch characteristics in the first two 32-ft logs of Douglas-fir trees.

METHODS

STUDY AREA

The study area was located in southwestern Oregon, USA, and extended from near the California border (42° 10' N) north to Cow Creek (43° 00' N), and from the Cascade crest (122° 15' W) to approximately 24 km west of Glendale (123° 50' W). Trees were sampled from plots established by the Southwest Oregon Forestry Intensified Research (FIR) Growth and Yield Project during the summer of 1983. Most plots consisted of Douglas-fir (Pseudotsuga menziesii (Mirbel) Franco) with varying mixtures of ponderosa pine (Pinus ponderosa Dougl.), grand fir (Abies grandis (Dougl.) Forbes), white fir (Abies concolor (Gord. & Glend.) Lindl.), sugar pine (Pinus lambertiana Dougl.), and incense cedar (Calocedrus decurrens (Torr.) Florin.). The study area covered an elevational range from 900 to 5100 ft. The climate is characterized by January mean minimum temperatures of 23° to 32° F, and July mean maximum temperatures of 80° to 90° F. Annual precipitation varies from 30 to 82 in., with less than 10 percent of the total falling during June, July, and August.

BRANCH DATA COLLECTION

A subsample of trees on each plot was felled for height growth measurement, stem sectioning, and crown sampling. Prior to felling, diameter at breast height (dbh) was recorded to the nearest 0.1 in, and total height and live crown height were estimated to the nearest 0.1 ft. Height to live crown was computed as the mean of height to full crown base and height to lowest contiguous live whorl, where full crown base was the lowest whorl with live branches around at least 3/4 of the stem circumference, and lowest contiguous live whorl was the lowest live whorl above which all whorls had at least one live branch (Maguire and Hann 1987). Also prior to felling, the directions of four crown radii were marked on the bole at breast height: the first two crown radii were measured along the line defined by the sample point and the center of the bole at breast height, and two other radii were located along the line perpendicular to the first.

After felling, a branch was selected along one to four of the marked crown radii per tree, each representing approximately the maximum radius on that side of the crown. Branch basal diameter was measured by diameter tape to the nearest 0.05 in., at approximately one branch diameter distance from the bole. Height of the branch to the nearest 0.1 ft was measured from ground level to the point where the branch center intersected the bole surface. Branch basal diameters ranged from 0.20 to 3.95 in., and were collected from 354 Douglas-fir trees ranging in dbh from 1 to 44 in., and in total height from 10 to 201 ft.

BRANCH DIAMETER PREDICTION MODEL

Numerous preliminary models were explored for predicting mean maximum branch diameter at crown base. The regression models screened included log-log models, weighted and unweighted linear models, and weighted and unweighted nonlinear models. The following weighted nonlinear equation was chosen for the present analysis on the basis of Furnival's (1961) index and residual plots:

$$BD = a_1\ DINC^{a_2}\ D^{a_3}\ H^{a_4}\ e^{a_5 H/D}$$

where BD is predicted mean maximum branch diameter (in), DINC is depth into crown (total height - branch height, ft), D is dbh (in), H is total height (ft), and a_1 through a_5 are regression coefficients with the following estimates and approximate standard deviations:

a_1 = 1.20102 (0.232499)
a_2 = 0.104259 (0.024470)
a_3 = 1.75787 (0.167275)
a_4 = -1.22857 (0.167984)
a_5 = 0.115682 (0.0237812)

Weighting factors of $1/D^m$ were applied during equation fitting, with m = 0, 0.5, 1.0, 1.5, and 2.0. A weighting factor of 1/D proved most appropriate.

MODELLING APPROACH

ORGANON is an individual-tree, distance-independent growth and yield model for the mixed conifer forests of southwestern Oregon (Hester et al. 1987). The model simulates stand development by updating the tree list by 5-yr growth periods with four major prediction equations, each of which is species specific: 1) height growth; 2) tree basal area growth; 3) height to live crown; and 4) probability of mortality. The following strategy was adopted for introducing branch diameter and whorl height predictions into the system:

1. Heights of every fifth annual whorl on each tree were obtained from five-year height growth predictions, then annual whorl heights were estimated by linear interpolation;
2. Height to live crown was predicted for each tree at the end of each five year growth period (Ritchie and Hann 1987). Annual crown recession was then retrieved by linear interpolation between previous and current height to live crown;
3. If height to live crown receded through a given annual whorl during any one year, the maximum branch diameter was predicted from the branch diameter prediction model;
4. At the end of the simulation, each tree was checked to determine whether the live crown had receded above 66.5 ft (top of the second 32-ft log). If height to live crown was below 66.5 ft, maximum branch size was predicted for each whorl up to this height, as long as the subject whorl was not further than 1/3 into the live crown;
5. Output was written to a tree list file that included annual whorl heights and corresponding mean maximum branch diameter predictions.

SILVICULTURAL REGIMES

Simulations were performed with data from a nine-yr-old Douglas-fir plantation with an initial density of approximately 484 trees per acre (tpa). Site index was 110 ft at 50 yrs, and all simulations were run for 65 years. Six different silvicultural regimes were implemented, with variations in both initial respacing and subsequent thinning regimes (Table 1). All thinnings were implemented proportionally across

Table 1. Six silvicultural regimes simulated in ORGANON to explore response of Douglas-fir branch diameter and distribution. Thinnings were specified in terms of Curtis's (1982) Relative Density (RD), where $RD = (\text{stand basal area})/(\text{quadratic mean diameter})^{1/2}$.

Regime	Initial density (tpa)	Thinning regime
1	121	None
2	242	None
3	242	RD55→RD35; no further thinning
4	484 (no respacing)	None
5	484 (no respacing)	RD55→RD35; no further thinning
6	484 (no respacing)	RD55→RD35; RD55→RD40; any subsequent thinnings RD60→RD40

Table 2. Final stand attributes for each silvicultural regime simulated with ORGANON.

Regime	Mean dbh (in)	Trees per acre	Basal area (ft^2/ac)	Volume (ft^3/ac)
1	23.8	83	257	12,308
2	20.3	131	293	14,486
3	19.9	119	256	12,686
4	18.1	181	322	16,075
5	17.3	193	315	15,809
6	17.5	148	248	12,443

the diameter distribution.

RESULTS

Final stand densities ranged from 83 tpa for Regime 1 to 193 tpa for Regime 5 (Table 2). The present analysis was restricted to the first two 32-ft logs from the largest 80 trees per acre remaining at the end of each simulation.

The mean of the four largest mean maximum branch diameters per log (BD_4) provided an index of branch size for each 32-ft log. Comparison of Regimes 1, 2, and 4 corroborates the expectation of a larger proportion of logs in larger BD_4 classes as initial spacing increases (Figure 1).

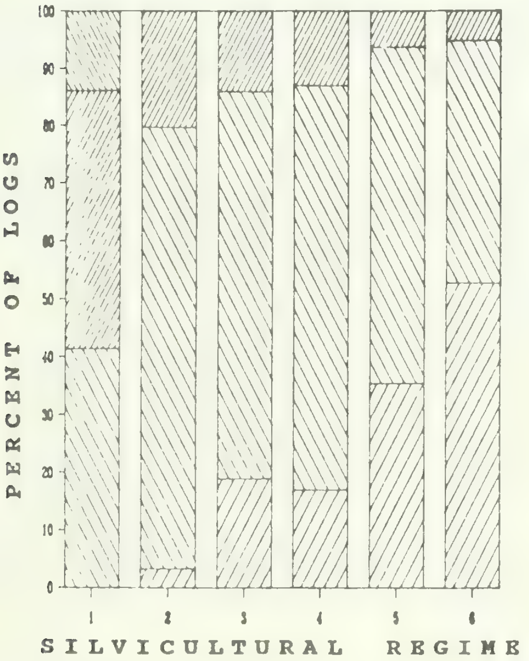

FIGURE 1. Percentage of first two 32-ft logs in each BD_4 class by silvicultural régime. ▨:1.1-1.5 in., ▧:1.6-2.0, ▨:2.1-2.5, ▩:>2.5.

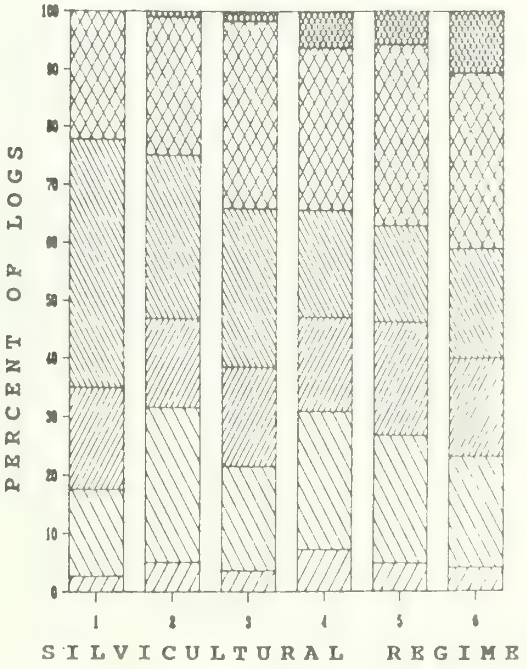

FIGURE 2. Percentage of first two 32-ft logs in each whorl frequency class by silvicultural regime. ▨: 12 whorls/log, ▧:13, ▨:14, ▤:15, ▦:16, ▩:≥17.

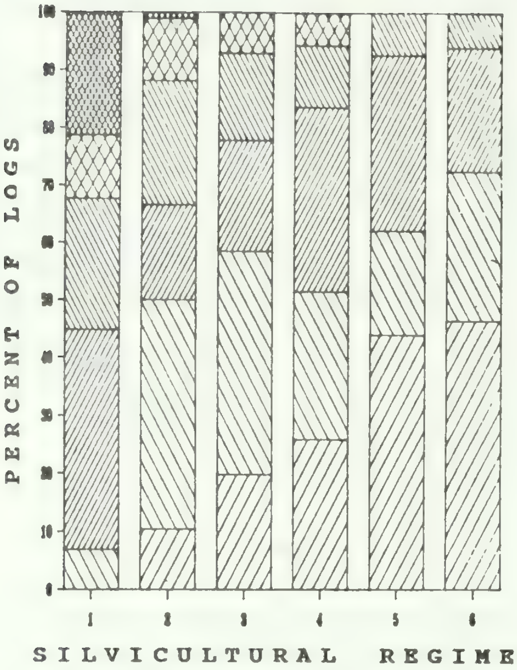

FIGURE 3. Percentage of first two 32-ft logs in each total branch basal area class by silvicultural regime. ▨: 20 in^2/log, ▨:21-30, ▨:31-40, ▨:41-50, ▨:51-60, ▨:≥61.

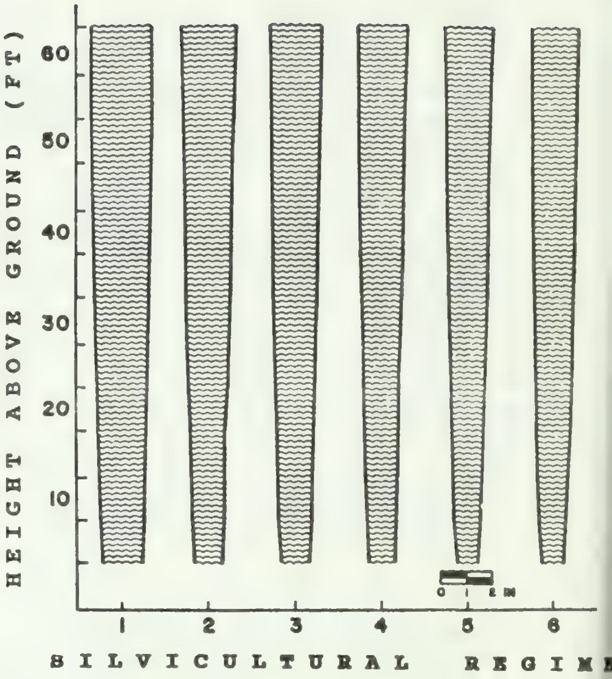

FIGURE 4. Mean maximum branch diameter by height for the average of the 80 largest trees per acre in each silvicultural regime.

In particular, note that Regimes 2 (242 tpa) and 4 (484 tpa) had, respectively, 79 and 87 % of the first two logs with BD_4 < 2.0 in., whereas the largest 80 trees per acre from Regime 1 (121 tpa) yielded only 42 % with BD_4 < 2.0 in. Regimes 5 and 6, which included commercial thinnings, yielded over two and three times as many logs, respectively, with BD_4< 1.5 as in unthinned Regime 4 (Figure 1).

Average whorl frequency was not influenced strongly by silvicultural regime; however, the proportion of logs with > 15 whorls increased from 22 % for Regime 1 to 41 % for Regime 6 (Figure 2). In general, maximum whorl frequency increased progressively from lower to higher initial densities and from lighter to heavier thinnings.

The sum of basal areas corresponding to all mean maximum branch diameters per log was computed as an index that integrated both branch size and whorl frequency. Again, the wider initial spacings and less intensive thinning regimes within an initial spacing produced larger percentages of logs with larger total branch basal areas (Figure 3). Since average whorl frequency was relatively little affected by silvicultural regime, this result reflected primarily the greater mean maximum branch diameters yielded by stands of lower initial density and less intensive thinning.

Finally, analysis of the vertical trend in mean maximum branch diameter revealed that all regimes exhibited similar relative increases in branch diameter with increasing height in the bole (Figure 4). Consistent with log distribution across branch diameter classes (Figure 1), mean maximum branch diameters were greater at all levels with lower initial density. Subsequent thinnings (Regimes 3, 5, and 6) had little effect on branch diameter even in the second 32-ft log.

DISCUSSION

Simulation results from ORGANON present no drastic departures from the previously documented trend of increasing mean maximum branch diameter with increasing initial spacing. The described approach demonstrates, however, a promising methodology for quantifying the consequences of silvicultural treatment on one aspect of wood quality for individual trees. Validation must still be performed, preferably by simulating a stand of known initial density and collecting appropriate branch data. The results, however, do agree quite closely with data from Douglas-fir plantations in Europe (Kenk and Unfried 1980).

At first glance, the smaller branch sizes associated with more intensive thinning regimes (3 vs. 2, 5 vs. 4, and 6 vs. 5) appear anomalous; however, since all thinnings were proportional across diameter classes, some larger dominants or codominants were removed, shifting the mean tree diameter downward with a concomitant reduction in mean maximum branch diameters. Thinning from below will also be explored in subsequent simulations to establish whether this result is indeed an artifact of the thinning method.

The increase in maximum whorl frequency (or reduction in minimum annual height growth) with closer initial spacing reflects a competition effect built into the height growth model. The increase produced by greater thinning intensity again largely reflects the type of thinning, since removal across all diameters shifted the lower limit of the largest 80 trees to smaller diameters and, presumably, to lower crown classes.

Vertical patterns in mean maximum branch diameter reflect initial density quite strongly, yet differences superimposed by commercial thinnings are barely detectable. In general, when the stand is thinned, branches persist deeper into the crown commensurate with the lower stand density. After the crowns close, crown base recession commences once again; but from this current crown base upward, the wider tree spacing is reflected in greater branch diameters. This effect in individual trees, however, is obfuscated in the present analysis due to the effects of proportional thinning on the mean of the 80 largest trees per acre.

As the effect of knot size and distribution becomes more fully understood, and as the accuracy of the described approach is honed to acceptability, results from this type of simulation can serve as input for prediction models and mill simulators developed by wood technologists. Directions for future work include refinement of the branch diameter prediction model, including more efficient estimation of parameters, as well as provision for retrieving logs from all commercial thinnings and from the full diameter range. Complete analysis of silvicultural alternatives will require accessibility to quantitative and qualitative characterization of all merchantable material produced during the rotation. Finally, further enhancement may be attainable by considering the number of branches per whorl as well as the range in diameters.

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AN INDIVIDUAL TREE TAPER SYSTEM FOR DOUGLAS - FIR IN THE INLAND - NORTHWEST

Pedro L. Real and James A. Moore[1]

ABSTRACT. A system of taper models was developed for second-growth managed stands of Douglas-fir (Pseudotsuga menziesii (MIRB) Franco) in the Intermountain Northwest USA. First a taper equation was fit for each tree in the sample, then parameters of the taper equation were predicted as functions of tree variables. This formulation allows the taper to vary as a result of management activities involving stand density manipulations. Validation of the taper system using an independent data set indicates that this approach performs better than other commonly used taper models.

INTRODUCTION

Taper functions, mathematical models for describing the shape and taper of tree boles, are effective for estimating three important attributes of a tree : 1.- Diameter at any point along the bole, 2.- Height to any predetermined diameter, and 3.- Volume between any two points on the bole. These attributes are important in partitioning a tree into a variety of products.

The lack of reliable taper information in the public domain for Inland Northwest second growth Douglas-fir prompted this study. Using data from trees destructively sampled by the Intermountain Forest Tree Nutrition Cooperative (IFTNC) an Individual Tree Taper System (ITTS) was developed.

Three analytical steps were involved in the creation of this system. The first two were the development and fitting of a taper model for each tree in the sample. Then a set of equations were built to predict the parameters of the individual tree taper equation as a function of tree variables.

DATA

A total of 1160 trees destructively sampled by the IFTNC in the Intermountain Northwest region were available for the fitting of the models. These trees were measured in 94 second growth, even-aged managed stands of Douglas-fir (Moore, 1984). The stands cover a broad range of ages, tree sizes, stand densities, sites, and stand conditions. Six geographic regions were included in the sample : 1. northern Idaho, 2. western Montana, 3. central Idaho, 4. northeast Oregon, 5. central Washington, 6. northeast Washington.

The sample tree data were edited for completeness, coding errors,

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monotonic decreasing function of the diameter sequence, and form abnormalities. After editing, a total of 1085 trees were suitable for further analysis. Table 1 shows the distribution of the sample by Dbh and total height classes.

TABLE 1. Distribution of the trees used in model development by diameter (Dbh) and total height classes.

Dbh	Total Height Class					
Class	< 50'	50'-70'	70'-90'	90'-110 '	>110'	Total
5"-10"	54	164	9	-	-	227
10"-15"	14	387	259	13	1	674
15"-20"	-	20	75	69	2	166
> 20"	-	-	4	7	7	18
Total	68	571	347	89	10	1085

The following variables were measured for each tree : Stump diameter (1 foot), Dbh, total height, diameter and height at the base of the active crown, and a variable number of diameters and heights along the bole (between 3 and 7). Along with the tree variables, environmental variables were recorded such as : geographic region, soil parent material, percent slope, aspect, elevation, vegetation series, and site index.

TAPER MODEL DEVELOPMENT

Several polynomial models fitted to each tree were analyzed and evaluated by measuring the quality of fit and prediction in terms of diameter and diameter square. The models were compared based on the average across all sample trees. A polynomial model that fit the differences between the squared ratio : $(d_i / Dbh)^2$ in a tree and $[(Th - h_i) / (Th -4.5)]^2$ that correspond to the squared ratio for a cone of the same tree Dbh and total height was found to be a good diameter predictor :

$$Y = b_1(X^3 - X^2) + b_2(X^8 - X^2) + b_3(X^{40} - X^2) \qquad (1)$$

where Y is $(d_i / Dbh)^2 - X^2$, d_i is diameter at a given height h_i, X is $(Th - h_i) / (Th - 4.5)$, Th is tree total height, and h_i is height to diameter d_i from the ground. All the diameters are outside bark. The transformations of X are similar to those in the taper equation derived for red alder by Bruce et al. (1968).

A geometric interpretation of the taper equation can be derived from Figure 1. Since the cone and tree have the same Dbh and Th, and the horizontal axis Z_i is defined as Th - h_i, the diameter of the cone at any point can be expressed by the equation

$$d_{i,cone} = k \cdot Z_i \qquad (2)$$

where k is a constant depending on Dbh and Th. The ratio of the diameter of the cone at a given height and Dbh is:

$$(k \cdot Z_i) / (k \cdot Z_{4.5}) = (Th - h_i) / (Th - 4.5) \qquad (3)$$

The square of the expression on the right is used in the definition of the independent variable of our taper model (1) that can be written as

$$Y = (d_{tree} / Dbh)^2 - (d_{cone} / Dbh)^2 \tag{4}$$

If an exponent of 1 or 3, is used in the ratio of the diameter of the cone and Dbh (second part of (4)) the differences with respect to a paraboloid or a neiloid can be obtained. In our case the use of a cone was always superior to the other alternatives.

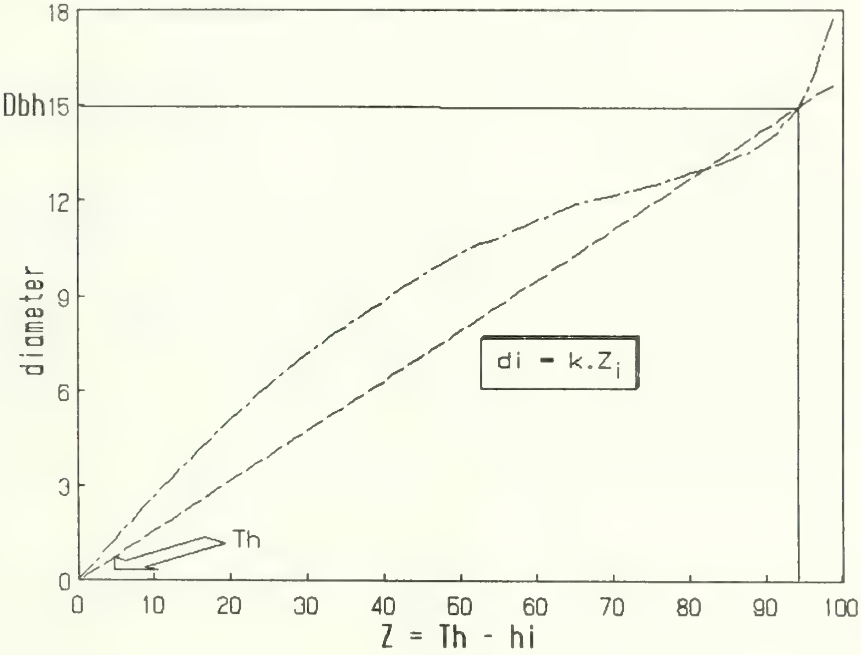

Figure 1. Tree and Cone Taper Curves.

The taper model developed (1) was fit to each tree in the data base. Two desirable conditions on it are : estimation of zero diameter when h_i is equal to Th, and Dbh when h_i is equal to 4.5 feet. Mean Squared Error (MSE) and Aggregate Difference (AD) were used as measures of prediction and bias respectively.

$$MSE = \sqrt{\Sigma(O_i - E_i)^2 / n} \tag{5}$$

$$AD = \Sigma(O_i - E_i) / n \tag{6}$$

where O_i is observed value, E_i is estimated value, n is the number of height-diameter measurements for a tree. These statistics were calculated for the whole tree as well as for five bole sections of equal length. A percent expression for (5) and (6) was obtained dividing each statistic by the mean of the observed value and multiplying by 100.

Average error and bias across all sample trees for the taper model using the least square estimate of each tree are presented in table 2.

Table 2. Error and bias analysis of the taper model : least square estimate of each tree (average across all trees).

Section	Diameter				Diameter^2			
	MSE		AD		MSE		AD	
(% Th)	In.	%	In.	%	In.	%	In.	%
0 - 20	0.02	0.18	0.00	0.01	0.71	0.30	0.13	0.01
21 - 40	0.08	0.83	-0.01	-0.08	1.89	1.65	-0.28	-0.17
41 - 60	0.09	1.16	0.00	0.02	1.66	2.33	0.12	0.01
61 - 80	0.20	4.06	-0.01	-0.82	2.14	8.10	0.07	-1.90
81 - 100	0.23	6.96	0.04	0.23	1.69	13.93	0.42	-0.34
over all	0.13	1.32	0.00	-0.01	1.75	1.52	0.03	0.00

Equation 1 can be written as :

$$d_i{}^2 = Dbh^2[X^2 + \{b_1(X^3 - X^2) + b_2(X^8 - X^2) + b_3(X^{40} - X^2)\}] \qquad (7)$$

Since Dbh for a given tree is a constant, the relative importance of each component (within the square brackets) of (7) at any height on the bole can be calculated. This is accomplished by dividing the contribution of each term by the absolute value of the sum. The averages for this calculation for all sample trees are shown in Figure 2.

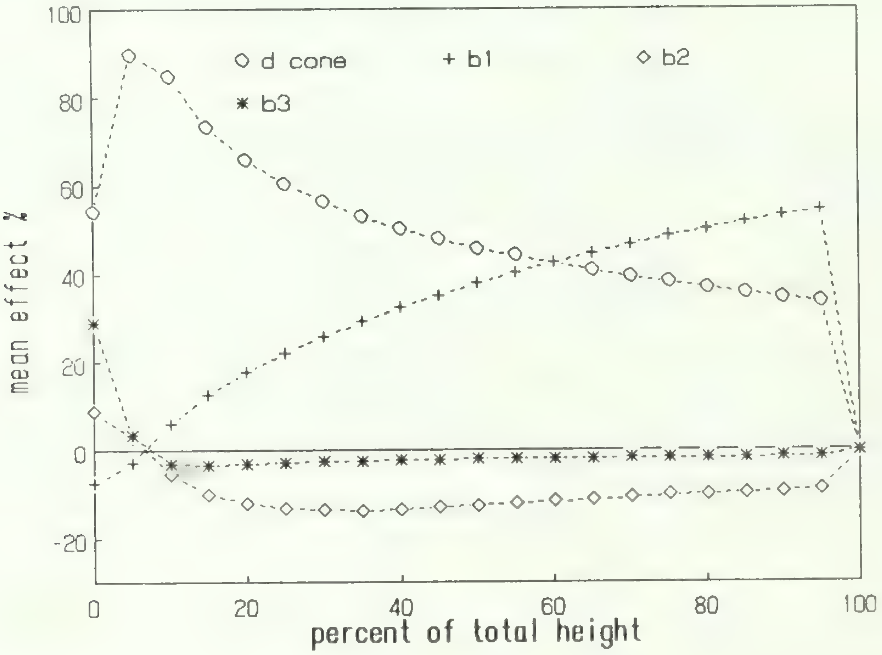

Figure 2. Coefficient of importance in the taper equation for every 5% of total height.

Two important conclusions can be derived from this graph : first; the $b_1(X^3 - X^2)$ term influences the diameter estimation along the whole bole; second, the term $b_3(X^{40} - X^2)$ has an important effect only in the bottom part of the tree (butt-swell) and practically none past 10% of total height. The use of the power (X^{40}) makes the model act as a segmented equation connecting the term when the value of X is close to or greater than 1 and disconnecting it when the value of X decreases. The selection of such a high power was done after analyzing the behavior of the equation with several high powers in that position. The power of forty was the smallest power that allows for a monotonically decreasing diameter function. b_2 also influences the shape of the curve mainly in the lower 30 percent of the bole.

Since model 1 was fit to individual trees a matrix of 1085 (sample trees by 3 (coefficients of the taper model) was available for further analysis.

PREDICTING THE COEFFICIENTS

The relationship of the mean of coefficients b_1 and b_3 with the mean of tree variables in twenty percentiles of b_1 and b_3 were graphically analyzed. The analysis confirmed what was evident in Figure 2; coefficient b_1, with a minor effect of b_2, controls the overall shape of the curve, while b_3 acts as a butt-swell coefficient. Figure 3 shows the relationship of b_1 with some tree variables.

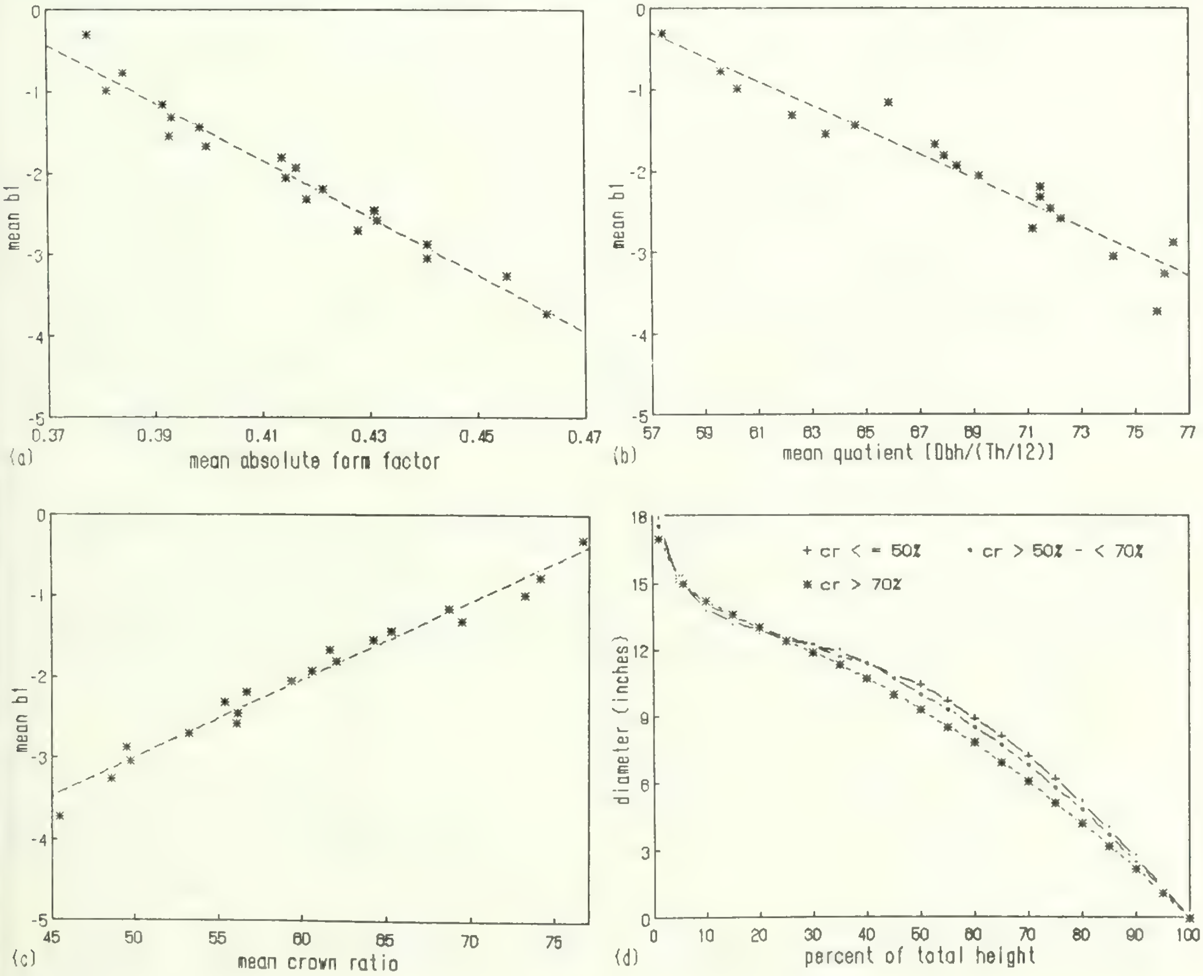

Figure 3. Relationship of regression coefficient b_1 to selected individual tree variables.

The relationship between b_1 and the Absolute Form Factor (AFF) clearly shows the association of lower AFF with greater values of b_1, indicating that conical shapes correspond to larger values of b_1 and more cylindrical shapes with smaller values of b_1. Confirmation of this assertion is found in Figure 3 (b) which depicts the relationship of b_1 with the shape quotient $Q = [Th / (dbh/12)]$ (Reed and Byrne, 1985). In agreement with Larson (1963), the taper model estimates smaller values of b_1 (better form) for trees with lower crown ratios and poorer form for large crown ratios Figure 3 (c). Figure 3 (d) shows the effect mentioned above for a tree 15'' Dbh and 80' tall. The taper curve was obtained with the average b_1 within three crown ratio strata; 1 : $\leq$ 50%, 2 : > 50% and $\leq$ 70%, and 3 : > 70%. Other important findings are : b_1 appears to be independent of Dbh, taller trees are associated with smaller values of b_1, an indication of better form; poor sites are associated with larger values of b_1 and vice versa (poor and better form respectively), and there is a positive relationship between elevation and b_1.

As shown in Figure 4, the b_3 coefficient is strongly associated with tree size. Small trees typically have less butt-swell than large trees, hence smaller values for b_3.

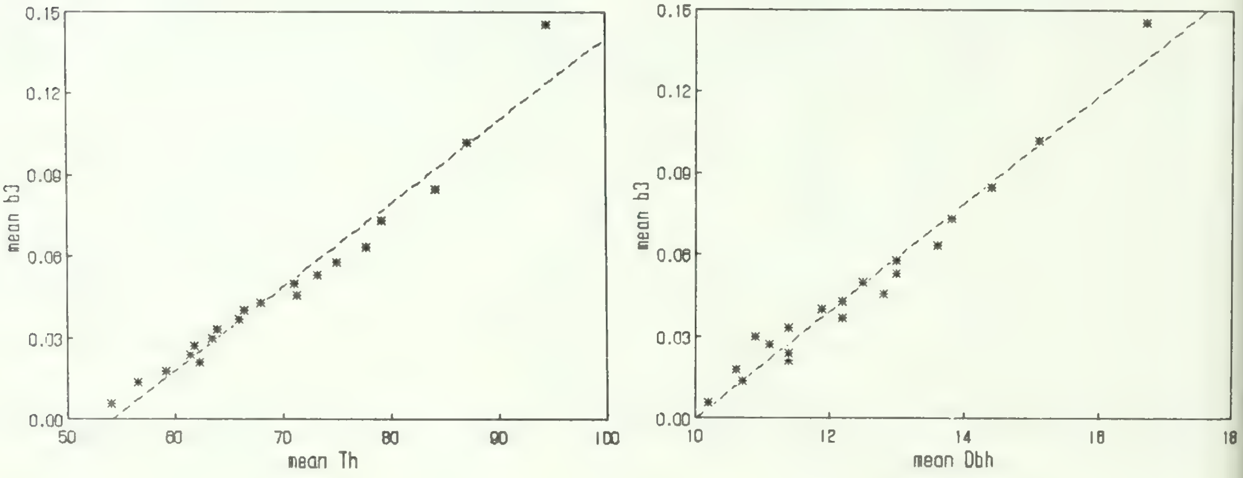

Figure 4. Relationship of regression coefficient b_3 with Dbh and Th.

To predict the coefficients of the taper model for individual trees, equations including only tree variables were explored. Three models including crown ratio (CR), shape quotient, and total height were built.

$$b_1 = a_0 + a_1Th + a_2Q + a_3CR \tag{8}$$

$$b_2 = a_0 + a_1b_1 \tag{9}$$

$$\ln(b3) = a_0 + a_1Th^{0.333} + a_2Q + a_3CR \tag{10}$$

To evaluate the prediction ability of the ITTS (M1) for diameter and diameter square, MSE and AD were calculated using taper model (1) with the parameters estimated by formulas 8 to 10. For the purposes of comparison, three taper models : Amidon (1984) (M2), Bruce et al. (1968) (M3), and Max and Burkhart's (1976) three parabolas with 2 joint points (M4) were fit to the same data set. Statistics (5) and (6) were calculated for the "fitting" data set, as well as for an independent data set. Table 3 displays the result of this analysis.

Table 3. Bias and error of diameter prediction for different taper equations (inches, fitting data set).

Tree Section	M1		M2		M3		M4	
(% Th)	MSE	AD	MSE	AD	MSE	AD	MSE	AD
0 - 20	0.39	0.06	1.09	0.12	0.38	-0.05	0.51	-0.04
21 - 40	0.36	-0.03	0.55	-0.43	0.37	-0.08	0.38	-0.06
41 - 60	0.39	-0.03	0.45	0.18	0.42	0.14	0.46	-0.04
61 - 80	0.38	-0.04	0.52	0.28	0.49	-0.13	0.53	-0.17
80 - 100	0.34	0.02	0.46	0.38	0.39	-0.21	0.36	0.08
over all	0.76	0.02	1.47	0.15	0.83	-0.14	0.94	-0.20

For the fitting data set, error's for the ITTS model (M1) are lower than those for the comparative models in each five section considered, as well as for the whole bole. The same result is true for bias.

An independent data set with 130 second growth Douglas-fir trees was used to test the models. The same tendency described for the fitting data set is depicted here. The result of the analysis for the independent data set is graphically displayed in Figure 5.

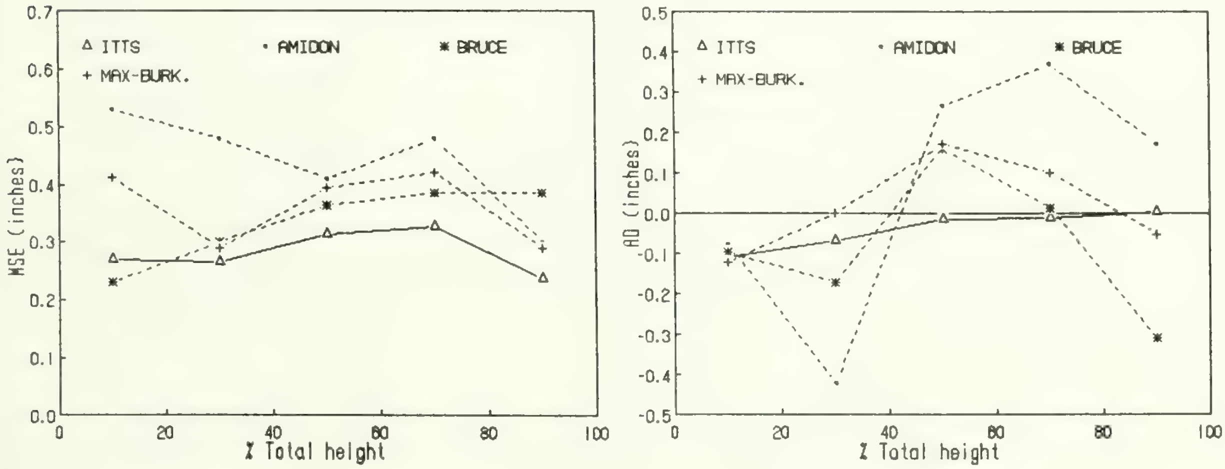

Figure 5. Bias and Error of diameter prediction for different taper equations (inches, independent data set).

CONCLUSIONS

ITTS has shown to be a good alternative in the study of tree form. The coefficients in the ITTS have meaningful interpretations that are in agreement with what is currently found in biological research regarding tree form.

The use of environmental variables to improve parameter prediction in the Individual Tree Taper Model (1) is currently under study. Site Index seems to have promise as a useful predictor of b_1.

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ESTIMATING CROWN BIOMASS OF SHADE TOLERANT AND INTOLERANT TREE SPECIES WITH A VARIABLE ALLOMETRIC RATIO

Gregory A. Ruark

ABSTRACT Attempts to model the impact of crown disturbances on stand-level growth are hampered by the difficulty of estimating the foliage biomass available for photosynthesis on an individual tree or the branch material available to deploy the canopy. The most pervasive allometric model for describing tree growth has been the power function, ($Y = aX^b$). Use of this function is predicated on the assumption that the proportional growth rate of some dimensional attribute of an organism is a constant allometric ratio (CAR) of the proportional growth rate of some other dimensional attribute of that organism. However, allometric ratios of crown components, when calculated from primary growth data, are often found to change sharply with increasing plant size.

An allometric model, ($Y = aX^b e^{cX}$), which incorporates a variable allometric ratio (VAR) that can change in a linear fashion, was fitted to crown biomass data for _Populus tremuloides_, _Acer rubrum_, _Picea glauca_, and _Pinus taeda_. Log-linear transformations of both models were compared to each other using DBH as the independent variable. The VAR model significantly improved the estimation of live branch and foliage biomass for the Populus and Picea species, as gauged by a higher coefficient of determination, lower standard error of estimate, and reduced bias in the residuals. The VAR model allowed for an allometric ratio which declined linearly with increasing stem size for Populus, but rose from an initially small value with increasing DBH for Picea. Additionally, the residual bias associated with foliar and branch estimates from the VAR model was less for all four species relative to the CAR.

The slope of the VAR appeared to be consistent for a given species. Slope estimates were indistinguishable for either foliage or branch biomass from two independent _Populus tremuloides_ data sets.

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INTRODUCTION

Concern over gauging the impacts of anthropogenic pollution on forests has resulted in a demand to more accurately define the relationship of crown characteristics of individual trees to the condition of their bolewood. This can be achieved thru three approaches:

1) collection of more crown data from the field
2) relating biologically relevant stem parameters, like sapwood cross-sectional area, to crown components
3) improving the mathematical functions used to relate stem measures to crown parameters

The collection of additional data to adequately represent a range of field conditions for important tree species should be pursued, but will take time. Measures of stem diameter taken at the base of the live crown or sapwood cross-sectional area taken at various positions along the stem have been shown to be better predictors of crown parameters than DBH (Maguire et al. 1987) and are integral components of a research program directed at understanding biological relationships. However, a preponderance of forestry data have been and will continue to be taken in terms of DBH. Consequently, there exists a need to improve the ability to mathematically relate DBH to crown characteristics. This paper focuses on this need.

Various forms of regression equations that relate the area, volume, or biomass accretion of one component of a tree to that of another more readily measured attribute of the same tree are termed allometric models. The general concept of allometry is restricted to relationships between attributes of an organism that are themselves biologically meaningful. However, the diameter of a tree at 1.35m from the ground (DBH), which is merely a convienent and arbitrary location to measure the stem, has conventionally been accepted in forestry as an independent variable in allometric equations used to predict the size of a tree component (Husch et al. 1972).

An allometric model of the form;

$$Y = aX^{b}\ E, \qquad (1)$$

where E is the error term and "a" and "b" are parameters to be fitted, was introduced to the forestry literature by Kittredge (1944). It found wide-spread usage in the prediction of foliage and branch biomass of individual trees from regressions on DBH. Ruark et al. (1987) noted that this model imposed a biologically unrealistic constant allometric ratio (CAR) when relating the proportional change in DBH to a porportional change in crown characteristics. These researchers introduced another term into the model to allow for a variable allometric ratio (VAR) that could change in a linear fashion. Their model took the form:

$$Y = aX^{b}\ e^{cX}\ E. \qquad (2)$$

The corresponding allometric ratio takes the form:

$$dY/Y = (b + cX)\ dX/X; \qquad (3)$$

When Equation (2) is transformed logarithmically,

$$\ln Y = \ln a + b \ln X + cX + E; \qquad (4)$$

the resulting equation differs from the log transform of Equation (1) by an additional term, "cX", which provides for a variable allometric ratio by adjusting the exponent, "b". When the estimate of parameter "c" is not significantly different from zero the "cX" term can be dropped and the equation reverts back to the logarithmic form of Equation (1). However, these researchers found that even when the "c" parameter was insignificant there was frequently a marked improvement in the distribution of model residuals attributable to Equation (4).

Although a VAR model was empirically shown to benefit the prediction of aspen (Populus tremuloides) crown components, its usefulness in predicting crown biomass for other tree species has not been demonstrated (Ruark et al. 1987). The objective of this paper is to determine whether a general need for a VAR model exists when using DBH to predict foliage and branch biomass for various tree species.

METHODS

Data sets representing several tree species were obtained from the authors of previous studies as follows:

1a.	Populus tremuloides	(Ruark et al. 1987;	45 trees)
b.	Populus tremuloides	(Pastor and Bockheim 1981;	10 trees)
2.	Pinus taeda	(Metz and Wells 1965;	19 trees)
3.	Acer rubrum	(Ker 1980;	48 trees)
4.	Picea glauca	(Young et al. 1980;	95 trees)

These data represent dominant and codominant crown classes, except for the presence of six intermediate trees in the Ruark et al. (1987) data. Details on sample collection and site characteristics are given by the respective references. Criteria for evaluating model performance were the coefficient of determination (R^2), standard error of the estimate (SEE),partial F statistic on the "c" parameter of the VAR, and patterns of residuals versus predicted values and DBH.

The General Linear Models (GLM) Procedure in SAS (1985) was used to fit the logarithmic equations for the CAR and VAR models to foliage and branch biomass data. Increases in residual variation at the upper end of the diameter range were markedly smaller for spruce than for the other less shade-tolerant species. Residual variances were weighted proportionally to DBH for spruce to counteract heteroskedasticity in logarithmic units. For aspen, only the data of Ruark et al. (1987) are detailed.

RESULTS AND DISCUSSION

The "c" parameter serves as an adjustment to the "b" exponent, and it was significant ($P<0.05$) in the VAR regressions on foliage and branch biomass for both aspen and spruce (*Picea glauca*) (Table 1). However, the "c" parameter was not significant for predicting crown biomass of loblolly pine (*Pinus taeda*) or red maple (*Acer rubrum*).

TABLE 1. Comparison of the CAR and VAR models for foliar and branch biomass prediction from DBH.

COMPONENT	FORM[A]	ln a	b	c	[B]	R^2	SEE[C]	CF[D]
ASPEN				(N = 45)				
Foliage	CAR	-4.34	1.87			.967	0.56	1.03
	VAR	-5.16	2.57	-0.06	($P<0.01$)	.977	0.39	1.02
Branch	CAR	-5.04	2.70			.982	3.07	1.03
	VAR	-5.62	3.19	-0.05	($P<0.01$)	.984	1.99	1.03
LOBLOLLY				(N = 19)				
Foliage	CAR	-4.32	1.89			.788	0.83	1.03
	VAR	-6.55	3.12	-0.01	($P<0.55$)	.796	0.84	1.04
Branch	CAR	-4.84	2.32			.846	2.81	1.04
	VAR	-4.80	2.28	0.002	($P<0.39$)	.852	2.89	1.04
RED MAPLE				(N = 48)				
Foliage	CAR	-2.81	1.81			.916	0.46	1.10
	VAR	-2.93	1.93	-0.01	($P<0.42$)	.917	0.47	1.10
Branch	CAR	-4.02	2.35			.938	6.51	1.10
	VAR	-3.35	1.95	0.04	($P<0.06$)	.943	5.58	1.09
SPRUCE				(N = 95)				
Foliage	CAR	-4.00	2.28			.877	4.60	1.21
	VAR	-3.35	1.66	0.06	($P<0.01$)	.886	3.90	1.21
Branch	CAR	-4.58	2.41			.883	6.30	1.22
	VAR	-3.67	1.43	0.10	($P<0.01$)	.904	5.13	1.18

A) CAR .... $\ln Y = \ln a + b \ln X$; VAR .... $\ln Y = \ln a + b \ln X + cX$
Where: Y = oven dry weight in kg of foliage or branches; X = DBH
B) Level of significance (1-tailed t-test) for parameter "c"
C) SEE = standard error of estimate in untransformed units
D) CF = correction factor for log transformation bias (Sprugel 1983)

Although the VAR model did not improve the R^2 or SEE for two of the species, it did improve the pattern of residuals in both foliage and branch regressions for all of the species examined. In the species where the VAR model was statistically superior to the CAR, foliar residual plots revealed that the CAR model tended to overestimate foliar biomass for large aspen trees, while underestimating the foliage of large spruce (Figure 1). The VAR model remained relatively unbiased throughout the range of DBH sampled.

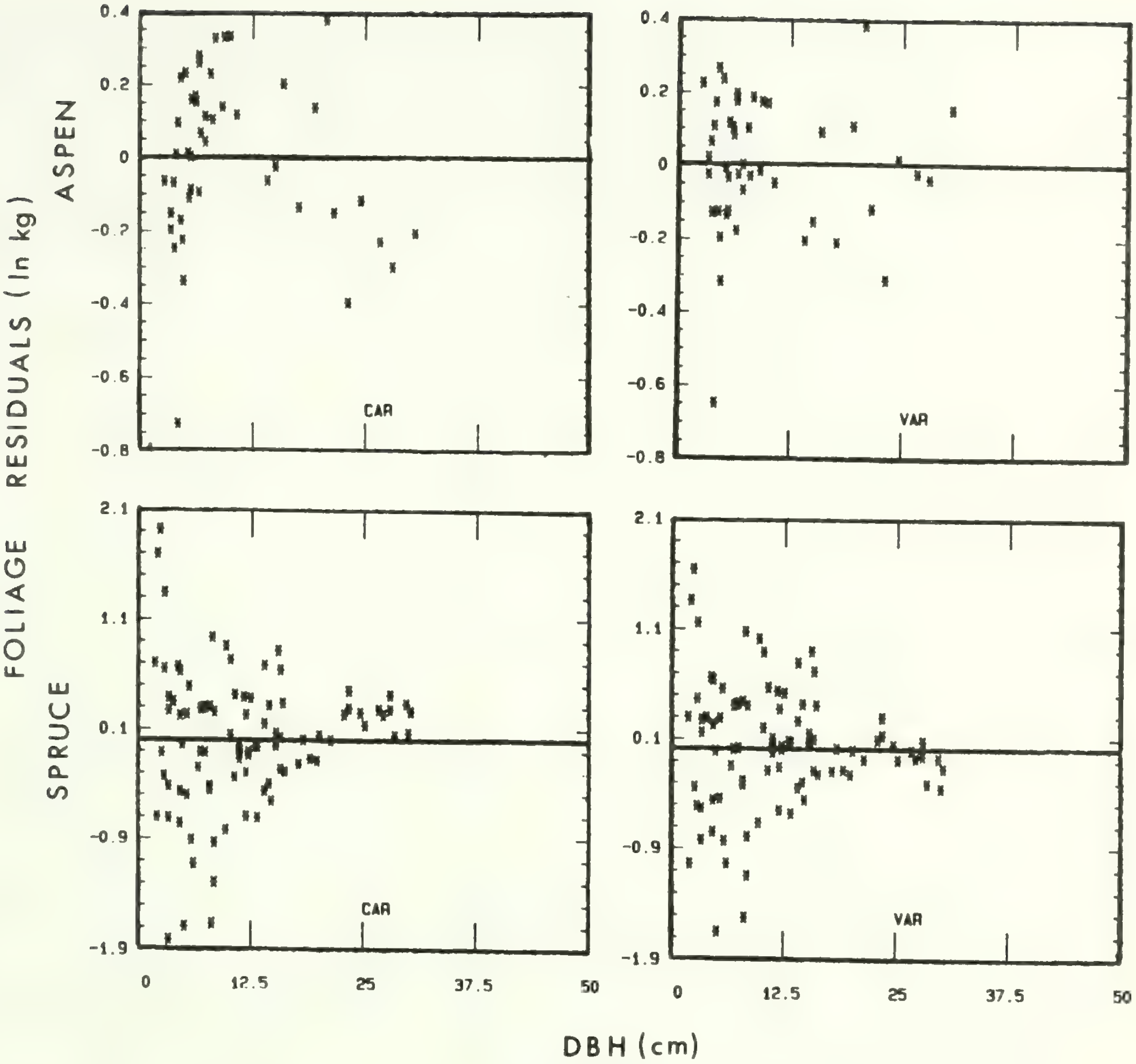

FIGURE 1. Foliage residuals (observed - predicted) over DBH for aspen and spruce.

Figures 2 and 3 show a species-specific trend in the slopes of the VAR as manifested by statistically different slopes among three groups (Fowells 1965): (1) the extremely shade tolerant spruce, (2) the intermediate tolerant loblolly and red maple and, (3) the extremely intolerant aspen. Among the four species, the slopes of the VAR for both foliar and branch biomass went from negative to positive with increasing shade-tolerance. This trend also occurred within conifer or deciduous catagories. As shade intolerant trees acquire new foliage at meristematic points, they also tend to prune their lower branches and crown interiors. This trade off results in successive net gains in foliage that decrease in magnitude as the stem increases in girth. Conversely, the slow rates of branch pruning and needle abscission in spruce result in increasing net gains in foliar biomass relative to sequential increments of DBH.

The "c" parameter of the VAR model was significant for both foliage and branch regressions for the two aspen data sets. The estimated slopes for the VAR were not significantly different at the 0.05 probability level when comparing the two aspen data sets for either foliage or branch estimates (Figures 2 and 3), suggesting biological relevance of the VAR slope parameter.

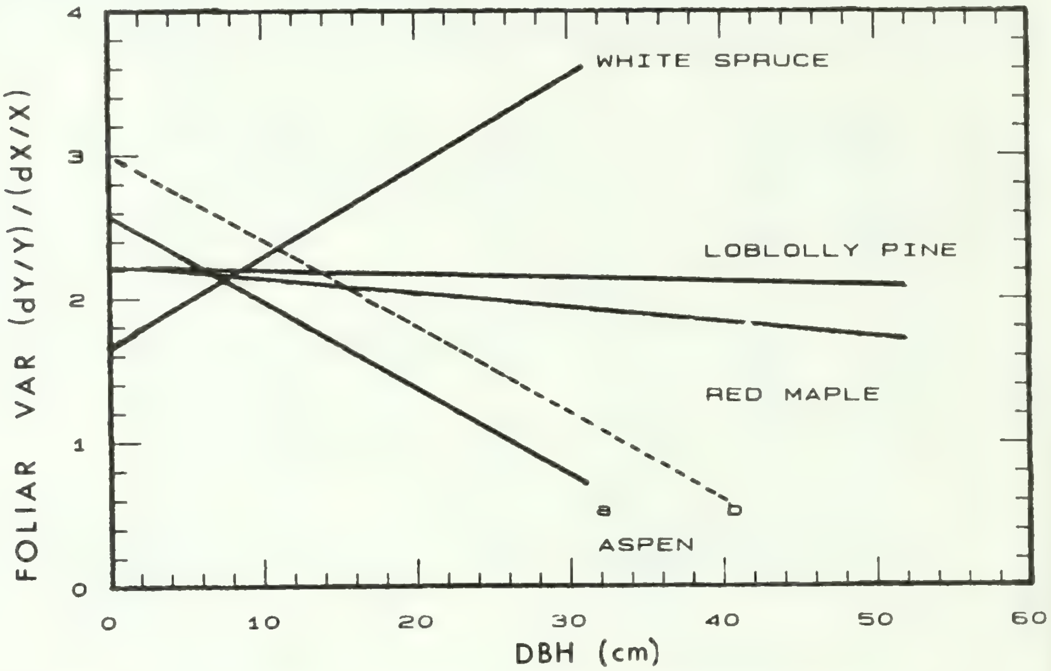

FIGURE 2. Variable allometric ratios for foliar estimation.

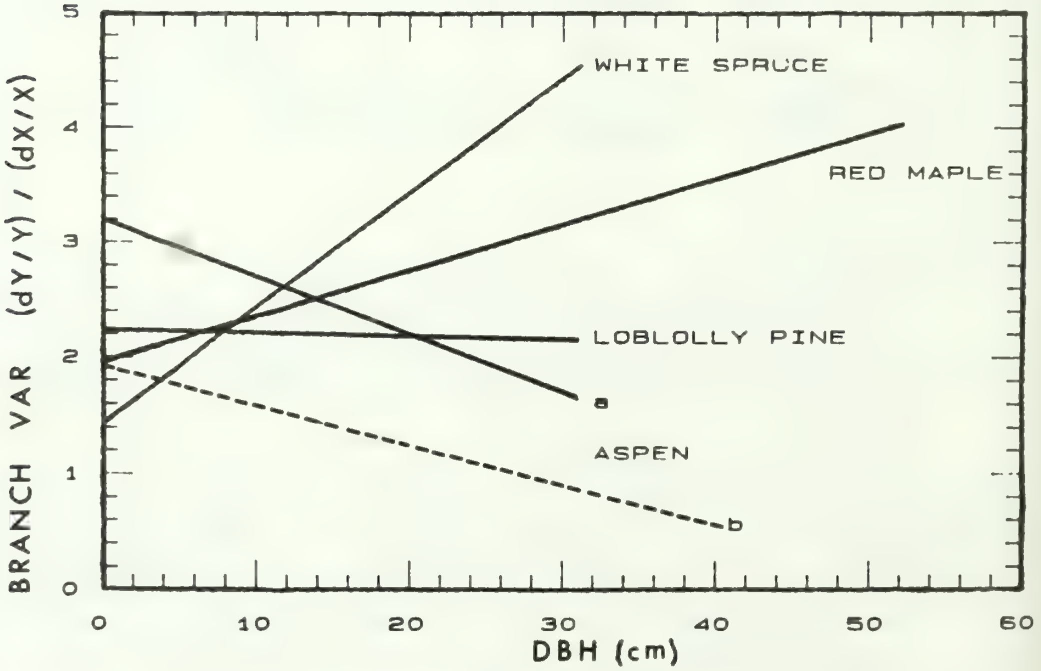

FIGURE 3. Variable allometric ratios for branch estimation.

The VAR model allows for a greater variety of curve shapes than the power function with its CAR. The predicted foliar biomass at a given DBH for aspen and white spruce (the two species where the "c" parameter was significant) are shown in Figure 4. Recall that the residuals in Figure 1 indicated that the VAR model was less biased than the CAR for both of these species. The VAR model allows for a rapid increase in spruce foliage biomass with increasing DBH, while the CAR model is unable to account for the faster increase in foliage biomass relative to DBH increment. The aspen curves illustrate the need for a VAR to allow for decreasing gains in foliar biomass with increasing stem size.

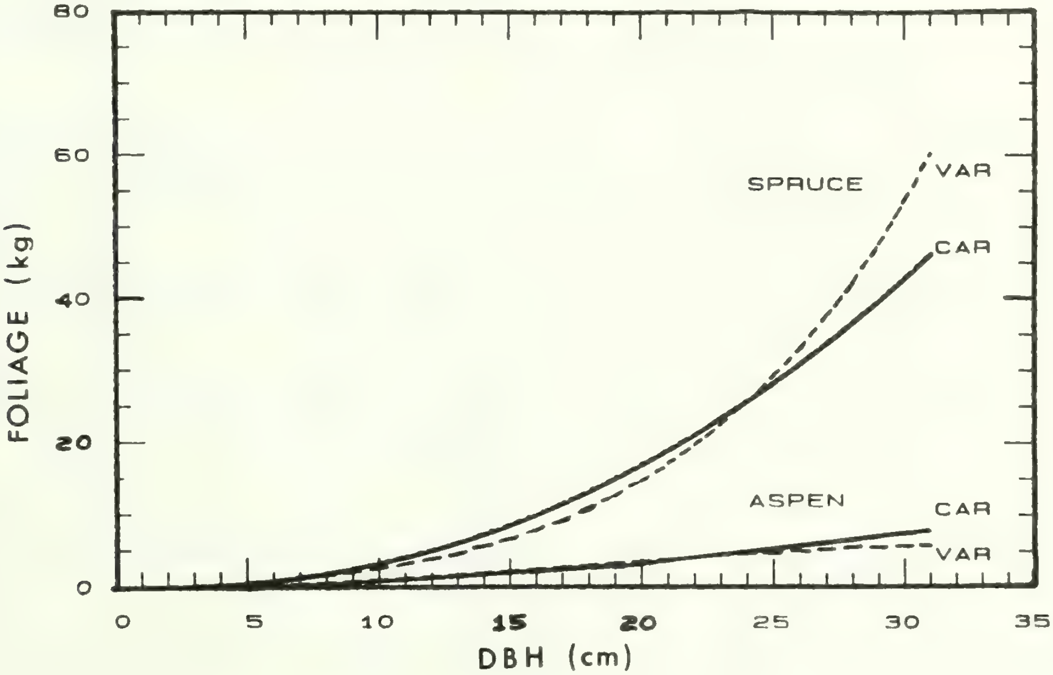

FIGURE 4. Plot of CAR and VAR model equations for aspen and spruce.

CONCLUSION

The need to use existant data and to gather extensive new data will result in the persistance of allometric regressions based on stem DBH. Parameterization of air pollution type models, which must account for crown factors, can not be met simply by gathering large data sets. It will also be necessary to improve the mathematics of relating stem dimensions to crown components. This paper demonstrates an improvement in predicting crown biomass from DBH by allowing for a linear variation in the allometric ratio which relates DBH to crown size. The method appears to be generally applicable to a variety of tree species.

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MODELING TREE QUALITY IN LOBLOLLY PINE PLANTATIONS

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ABSTRACT. Tree quality has gained increased importance in the management of loblolly pine plantations. This has become particularly apparent as larger proportions of solid wood products are sawn from plantation grown trees. Smaller stem sizes and higher proportions of juvenile wood resulting from economically necessitated short rotations amplify the deleterious effect of stem defects such as knots and sweep on product yield and quality. Factors leading to the development of sweep and its impact on lumber yield and value are discussed. An approach to modeling stem sweep with second order differential equations is presented.

INTRODUCTION

Tree quality has not been of great concern in the production of Loblolly and other Southern pines. Lack of concern has primarily been due to the abundance of large, old (18+ inches Dbh, in excess of 65 years) timber that existed in the past. Most of those stands have either been cut or now have a higher use other than timber production. The plantation grown timber replacing them has characteristics of small stem size and high proportions of juvenile wood that are associated with short rotations. This has been accompanied with a milling technology directed toward high productivity rather than product quality. As a result, much higher quality Canadian lumber is preferred by most users of softwood lumber.

The apparent overcutting currently existing in Canada will lesson its capacity to supply solid wood products, likely increasing the demand for the production of solid wood in the South. Given that long rotations, the source of high quality timber in the past, are no longer economically feasible, the development of silvicultural and processing systems for producing high quality wood on short (<= 35 years) rotations will be required to satisfy the demand. A requisite to their development is an understanding of the characteristics that affect wood quality and the ability to model their impact and development.

THE DEVELOPMENT AND CHARACTERISTICS OF SWEEP

The development and characteristics of sweep are covered in great depth by Timell (1986). The following are some of the relevant points. The propensity to sweep, though highly heritable, is strongly related to the physical environment in which the tree develops. It is particularly common in plantations where poor planting practices such as J-rooting are prevalent. Particularly if the stand is under intensive management, the

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stem and crown develop faster than the root system can grow to support it and the tree leans as a result. Sweep then arises from the geotropic response by the tree to the lean. The increased concentration of auxins on the downward side of leaning stems causes increased growth rate (the formation of compression wood) as the tree "attempts" to right itself relative to gravity. This process can produce trees that gradually become vertical, resulting in various degrees of "butt sweep" or trees that "overcorrect," resulting in a sinusoidal shape or "wobble". The resultant effects are eccentric logs characterized by uneven growth rings about the pith and the associated compression wood which has up to ten times the longitudinal shrinkage of "normal" wood. When straight lumber is sawn from sweepy logs, the presence of compression wood combined with the accompanying disorientation of growth rings produces lumber with extremely poor stability.

THE EFFECT OF SWEEP ON LUMBER YIELD AND VALUE

Sweep affects the recovery (board feet of lumber sawn per cubic foot of log), the size (length and width), and dimensional stability of lumber that can be cut from logs. Table 1 was developed from a relationship developed by Bridgwater (1984). The rather significant impact of sweep on recovery is obvious, particularly with small stems. Each additional inch of sweep on 6 to 10 inch logs decreases the percent recovery an incremental 10 to 20 percent.

TABLE 1. Percent recovery[1] as a function of small end diameter (SED) and sweep.

SED (inches)	SWEEP (inches) 0	1	2	3	4
18	100	98	95	93	90
16	100	97	94	91	88
14	100	96	92	88	84
12	100	95	89	84	79
10	100	92	85	77	69
8	100	88	76	64	52
6	100	79	57	35	14

[1] Actual recovery relative to recovery with no sweep.

The effect of sweep on recovery can be minimized to a certain extent by cutting sweepy logs to shorter lengths. The impact of length on value of the final product can be very substantial as illustrated by Table 2. The lumber values were taken from Timber Mart South (1987), and log values were determined assuming a 100 dollars per Mbf processing cost. Additional handling costs associated with shorter lengths are ignored. Much of the gain made in increased recovery can be lost in lower final product value.

Table 2. Effect of length on value of 2x4 Grade 2 & Btr Dimension lumber and delivered sawlogs.

Product	8	10	Length 12	14	16
Lumber	247 (-22)	282 (-11)	290 (-9)	289 (-9)	317
Sawlogs	147 (-33)	182 (-16)	190 (-12)	189 (-12)	217

[1] The number in parentheses is the percent reduction in value from the next longest length.

The above calculations assumed no loss in grade due to sweep. The compression wood formed in association with sweep and the growth ring disorientation that occurs in sawing sweepy logs can cause lumber downgrade due to the resultant crook, twist, and cup. The obvious need is the capability to model grade yield in addition to gross lumber yield.

APPROACHES TO MODELING TREE QUALITY

The most common approach to modeling grade yield has been the development of tree and log grades. Lumber grade is then predicted as a function of log size and grade. Log and tree grades have been developed for loblolly pine by Schroeder et. al. (1968). Using their rules, the grade of the tree is determined by the number of clear faces on the butt log. The butt log is divided into 4 "faces" one quarter the circumference extending the length of the log. The grade is determined by the number of clear faces present. For example:

Grade	# Faces
A	3 or 4
B	1 or 2
C	none

After the tentative grade is established, if sweep is more than 3 inches and equals or exceeds one-fourth of the Dbh, then the log is downgraded one grade.

Product yield and subsequent value are then based on mean product yields or regression equations developed from mill studies on logs from a range of size/grade combinations.

There are several limitations to grading procedures of this type. A tree can be given a specific grade for more than one reason. It can be downgraded because of knots (faces) or because of sweep. Knots and sweep have different effects on product yield and quality. Tree grades only indicate the presence or likely absence of interior defects in the tree, not their size and distribution within the each log. An additional problem is predicting the change in grade over time. A tree may "grow out" of one defect but not the other. A more pragmatic problem with respect to pine plantations is that 30-year old loblolly pines don't have clear faces. An additional problem with empirical grading procedures is that the products for which they were developed may for be no longer produced.

For the above reasons a more desirable approach would be to model the physical process from which the defect arises and subsequently the milling process producing the desired final product.

MODELING STEM SWEEP WITH SECOND ORDER DIFFERENTIAL EQUATIONS

A potential approach to modeling sweep is based on a second order differential of the form:

$$d^2x/dy^2 + A\, dx/dy + B\, x = C \qquad (1)$$

where conceptually at height **y**, **x** represents the deviation from straight, **dx/dy** the lean of the tree, and **d^2x/dy^2** the geotropic response of the tree to lean. **A**, **B**, and **C** are theoretically derived or estimated from empirical data.

The results of this approach are presented in Figure 1. (a) is the stem shape of an actual tree, (b) the predicted shape using equation (1), and (c), the predicted shape based on the assumption of straightness implied by commonly used taper functions.

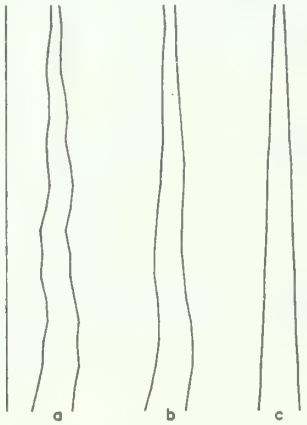

Figure 1. Comparison of (a) actual stem shape, (b) predicted stem shape using a second order differential equation, and (c) predicted shape for straight stems.

The actual deviation from straight for the first log was 2.5 inches and the predicted deviation 2.0 inches. The top diameter of the first log was 8 inches. Using Table 1. the percent recovery for the but log of the three "trees" in Figure 1. are as follows:

(a) actual	70
(b) predicted	76
(c) straight	100

The yield based on the assumption of straightness over predicts the actual by 30 percent. The differance between actual and predicted is 7 percent.

This simple example ignores lumber quality. Future efforts will include modeling the zone of compression wood within the tree and the associated eccentricity. This will facilitate including the effect of compression wood and growth ring orientation in simulating lumber grade yield and recovery.

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EXPERIMENTAL DESIGN AND EARLY ANALYSES FOR A SET OF LOBLOLLY PINE SPACING TRIALS

by

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ABSTRACT. In the spring of 1983, a set of loblolly pine (Pinus taeda L.) spacing trials was established in the Coastal Plain and Piedmont regions of Virginia and North Carolina. The experimental design chosen was nonsystematic allowing the spacings to vary in two dimensions on a factorial basis. This layout creates plots of each spacing that vary in size with equal numbers of trees per plot. The plots form a compact block in which main effects are confounded with the row and column positions of the block. This experimental design and the selected spacings offer opportunities to examine the effects of spacing and density on tree growth, survival and stem form. Analyses of data through age four indicate that lower crown ratios are occurring in the denser spacings and more elliptical crown shapes are occurring in the rectangular spacings.

INTRODUCTION

Loblolly pine (Pinus taeda L.) is one of the most important timber species in the Southern United States. Plantations of loblolly pine are managed for a wide variety of wood products. Because loblolly pine is a relatively intolerant species, the amount and types of products obtained from these plantations are affected greatly by stand density. Therefore, controlling planting density has long been recognized as one of the most important tools available to forest managers for achieving particular product yields from loblolly pine plantations.

To fully understand the effects of density, it is necessary to control planting spacing from plantation initiation holding other factors constant and then observe the stand through rotation. Most of the growth and yield data being collected and analyzed for loblolly pine, however, come from plots established in existing stands where the initial density was not deliberately varied over a wide range. Designed experiments where initial spacing is controlled carefully and varied widely are needed to answer questions about the optimal number of trees to plant for various product objectives. In addition, spacing studies can provide valuable information about juvenile growth, mortality and density effects on height and diameter growth. Data from spacing studies also offer opportunities to test hypotheses about a number of growth and yield relationships that cannot be addressed with survey-type data.

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The purpose of this report is to describe the experimental design and field procedures used to establish a set of loblolly pine spacing trials in Virginia and North Carolina and to present some early results from these trials.

EXPERIMENTAL DESIGNS FOR SPACING STUDIES

Over the years, many different spacing studies have been established for a wide range of tree species. Evert (1971) reviewed many of these studies. Rather than review individual studies, this section highlights the selection and application of experimental designs to spacing studies in forestry and discusses the perplexing dilemmas that often exist in making such selections.

The advantages of randomized block designs for spacing experiments are well known. The greatest advantage is that randomization provides, if the plot-treatment additivity condition holds, unbiased estimates of the variance of treatment effects and unbiased estimates of the mean. This, plus the assumption that errors are independent and normally distributed, allows analysis of variance procedures to be used for testing hypotheses. Regression techniques can also be used for examining relationships along response surfaces if the levels of treatment span a broad enough range. Designs that utilize a fixed plot size different number of trees are best for analyzing yields per unit area and the plot-to-plot environmental variation should be more homogeneous than with variable plot size same number of trees designs. These advantages, however, are often offset by the large number of trees necessary to effect such designs.

The number of measurement trees can be held to a reasonable level by using variable plot size same number of trees designs. These designs, however, have the disadvantage of heterogeneous plot-to-plot variation and the unequal-sized plots of different shapes are often difficult to fit together into a compact, contiguous block. Both types of randomized block designs usually require establishing an inordinate number of guard trees between plots which results in block sizes that are difficult to establish and replicate even on the most uniform sites.

In recent years, systematic designs have received much attention because of their practical advantages over randomized block designs. The set of systematic designs first proposed by Nelder (1962) and later modified by Bleasdale (1967) have a number of attractive features which make them useful for forestry spacing studies. The chief of these is that they permit the evaluation of a wide range of spacings while making efficient use of plant material and field space. Nelder designs are particularly useful if the study goals are primarily explanatory. In such cases, response surface analysis using regression techniques would be the primary tools of analysis.

The main shortcoming of Nelder designs is that testing hypotheses using analysis of variance techniques is not appropriate because the necessary assumptions concerning the error terms cannot be met. Nelder designs are also not well suited to examining optimum spacings or rectangularity because of asymmetric density around individual trees.

Clearly, there is not one experimental design that can be called "best" for every application. As Mead (1979) pointed out, the proper choice of experimental design depends on many factors specific to the situation which must be carefully weighed by the researcher. Among the most important are:

(a) the goals and objectives of the study. If the explanation of relationships is of primary importance using regression techniques, then systematic designs are most efficient. If hypothesis testing is of interest, then some type of randomized block design is appropriate.

(b) the particular spacings of interest. If the effect of rectangularity on yield and individual trees is important, block designs will likely be most useful.

(c) the practical limitations of space and plant material. If these factors are limited such that an adequate number of measured trees and guard trees cannot be established and remeasured in an economical way using a block design, then systematic designs appear to be the logical alternative.

(d) knowledge about future uses of the study. If subsequent intermediate treatments such as thinning, pruning or fertilization might be applied, then every effort should be made to select a design that can accomodate such treatments. In the long run, the most useful designs are likely those that are the most flexible.

Even for a particular application, it is unlikely that one specific design will emerge as the clear favorite over all others in every respect. Some type of tradeoff between the considerations listed above and perhaps others will often have to be accepted. A design that incorporates many of the desirable features of systematic and randomized block designs has been proposed by Lin and Morse (1975).

EXPERIMENTAL DESIGN FOR A SET OF LOBLOLLY PINE SPACING TRIALS

In 1983, a set of loblolly pine spacing trials was established under the auspices of the Loblolly Pine Growth and Yield Research Cooperative at Virginia Polytechnic Institute and State University. The design selected was a non-systematic design presented by Lin and Morse (1975). In this design, spacings are randomly assigned in two dimensions to row and column positions which results in a factorial arrangement with equal numbers of trees per plot and different plot sizes and shapes. The plots fit together into a compact block which can be replicated at each site. Each plot is separated from neighboring plots by a suitable number of guard trees that act as buffers to minimize the effects of neighboring plots.

For this study, a spacing factor (F) of 4 feet (1.22 meters) was selected and four spacing levels of this factor (1F, 1.5F, 2F and 3F) were incorporated into the design. Each spacing is represented by seven rows and seven columns of measurement trees that form a 49-tree measurement plot. Each measurement plot is buffered from adjacent plots by three guard trees and three rows and columns of guard trees surround each block. Thus, each block consists of sixteen plots developed from the factorial arrangement of the four spacing levels applied randomly to the row and column positions. The sixteen plots in each block are: 1F x 1F, 1F x 1.5F, 1F x 2F, 1F x 3F, 1.5F x 1.5F, 1.5F x 2F, 1.5F x 3F, 2F x 2F, 2F x 3F, 3F x 3F, 1.5F x 1F, 2F x 1F, 3F x 1F, 2F x 1.5F, 3F x 1.5F and 3F x 2F. Thus, each block has one plot of each square spacing and two plots of each rectangular spacing. Including guard trees, each block occupies approximately 2.25 acres (0.907 hectares). Figure 1 shows the arrangement of plots and guard trees in a typical block.

This design seems to offer an agreeable compromise between the statistical advantages of some designs and the practical advantages of others. From a statistical perspective, the non-systematic arrangement provides unbiased estimates of the means and allows analyses to be performed using analysis of variance techniques as well as analyzing response surfaces with regression methods. In this regard it has many of the advantages associated with randomized block designs. The unequal-sized plots, however, can create difficulties with the error variance structure since the ranges of environmental variation may be different for different sized plots. This shortcoming can be minimized by carefully selecting sites that are as uniform as possible within a block and by prudent use of guard trees.

From a practical standpoint, the plaid design discussed here places the plots in a compact block that makes more efficient use of land area and plant material than block designs that utilize unequal numbers of plants in plots of equal area. This is an important consideration because of the significant maintenance and remeasurement costs associated with long-term forestry spacing studies.

The choice of spacing levels (1F, 1.5F, 2F and 3F) produces plots that span a broad range of initial densities from 302 to 2722 trees per acre (746 to 6723 trees per hectare) and present opportunities to examine some important density and spacing relationships. One relationship is the effect of different spacing rectangularities at the same density. The 1F x 3F and the 1.5F x 2F spacings both have the same density and thus the same growing space per tree. However, since the allocation of the growing space is different, rectangularity effects can be evaluated. The opposite situation can also be examined by considering the 1F x 2F and the 1.5F x 3F spacings which have the same rectangularity (1:2) but different densities.

The choice of spacing levels also leaves open the possibility for applying intermediate silvicultural treatments. For example, at some point one of the 1.5F x 3F spacings could be thinned to a 3F x 3F spacing by removing every other row. Then the effects of thinning from 1.5F x 3F to 3F x 3F could be compared to the original 3F x 3F spacing plot.

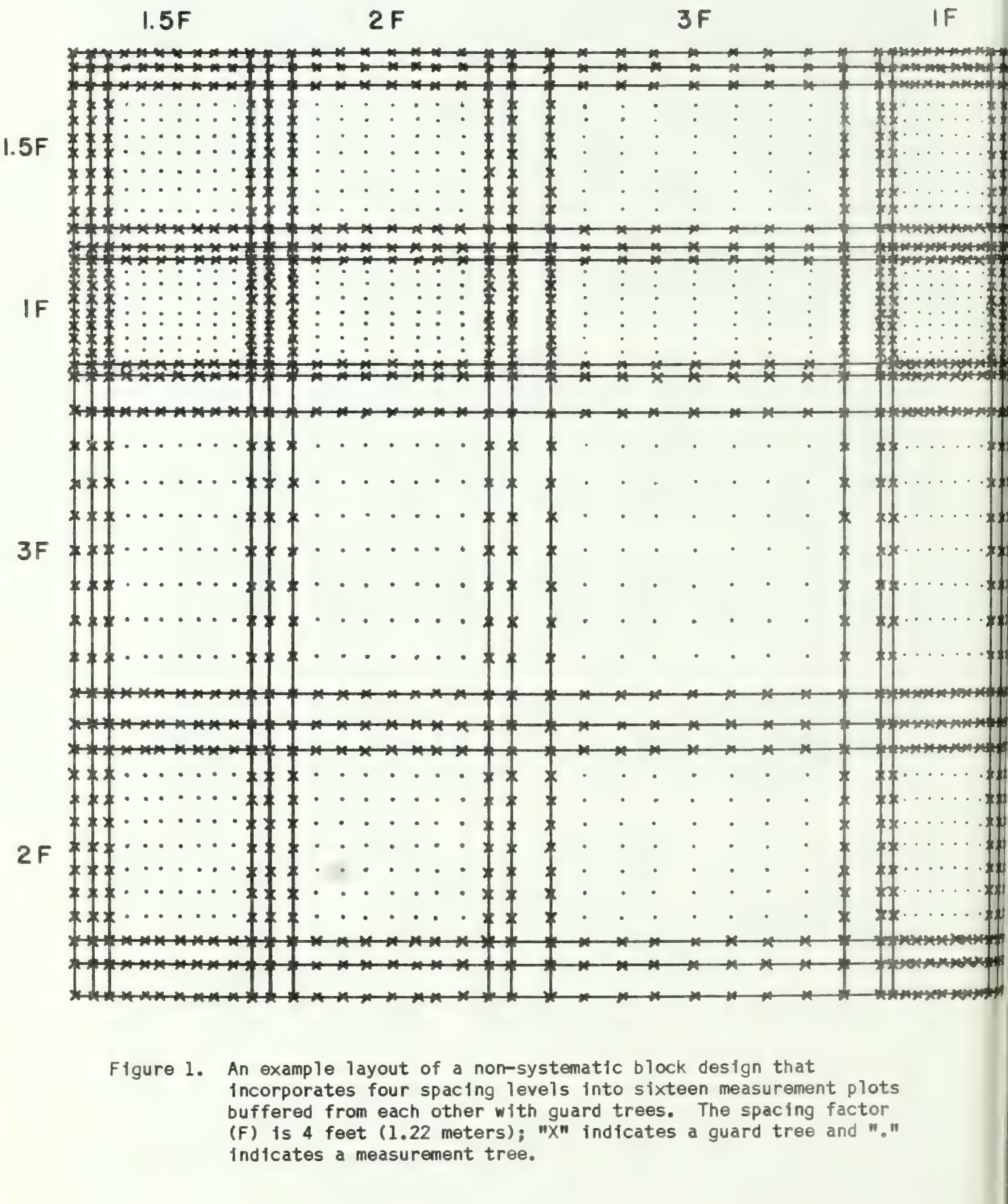

Figure 1. An example layout of a non-systematic block design that incorporates four spacing levels into sixteen measurement plots buffered from each other with guard trees. The spacing factor (F) is 4 feet (1.22 meters); "X" indicates a guard tree and "." indicates a measurement tree.

FIELD PROCEDURES

In the Spring of 1983, four locations were selected in Virginia and North Carolina for establishment of the spacing trials. Two of these locations are situated in the Piedmont physiographic region and two in the Coastal Plain region. All locations were cutover areas that received an operational chop and burn site preparation treatment prior to planting. At each location, three blocks were established on the most uniform areas available.

The planting stock used was genetically improved 1-0 loblolly pine seedlings. All seedlings planted at each location were lifted from the same nursery bed at the same time. At time of planting, each seedling was examined and only those that appeared healthy and vigorous were planted. Outplantings were established beside each block as replacements for first-year mortality. Three times during the first year each location was visited and mortality replaced with the outplantings. These replacement trees were flagged so that they could be separated from the original seedlings in future analyses.

After one year, three of the four locations had initial survival in excess of 90 percent. One Coastal Plain site had only about an 80 percent survival rate so all trees were removed at this location and the three blocks reestablished in the Spring of 1984. Therefore, this location is one year younger than the other three.

From establishment, both herbaceous and woody competing vegetation have been controlled using chemical herbicides. The herbicides have been applied annually as a directed spray using backpack sprayers. Competing herbaceous vegetation was treated through age two and competing woody vegetation every year to the present. The chemical control helped achieve high initial survival of the pines and allowed the pines to quickly gain control of the site. This will help reduce the extraneous variation due to the effects of interspecific competition in future analyses.

Three locations are now into their fifth growing season and one Coastal Plain location is into its fourth growing season. Annual measurements have been collected during the dormant season on all measurement trees. The data collected include groundline diameter, total height, height to the base of the live crown, crown width within the row, crown width between the row and maximum crown width. In addition, each tree was examined for signs of disease or damage and assigned an appropriate vigor code. By age four, crown closure had been achieved in the closer spacings and it was apparent that intraspecific competition had begun. It is planned to continue annual measurements as long as field conditions allow. Then, a less frequent measurement schedule will be initiated.

SOME ANALYSES AND PRELIMINARY RESULTS

The total height, groundline diameter and crown height and width data were examined for the three locations that had completed four growing seasons in the field. These relationships were similar for the three sites. Therefore, results are presented for the three blocks at one of the Piedmont locations established on what is expected to be an average site (site index of approximately 60 feet (18.5 meters) at age 25). It is

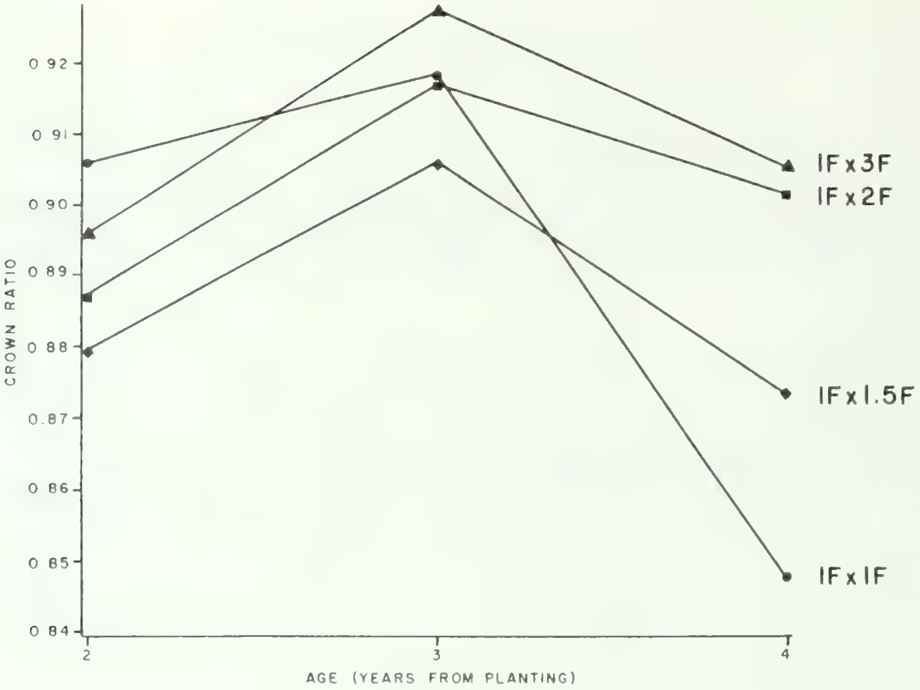

Figure 2. Mean crown ratio for the 1F x 1F, 1F x 1.5F, 1F x 2F and 1F x 3F spacings.

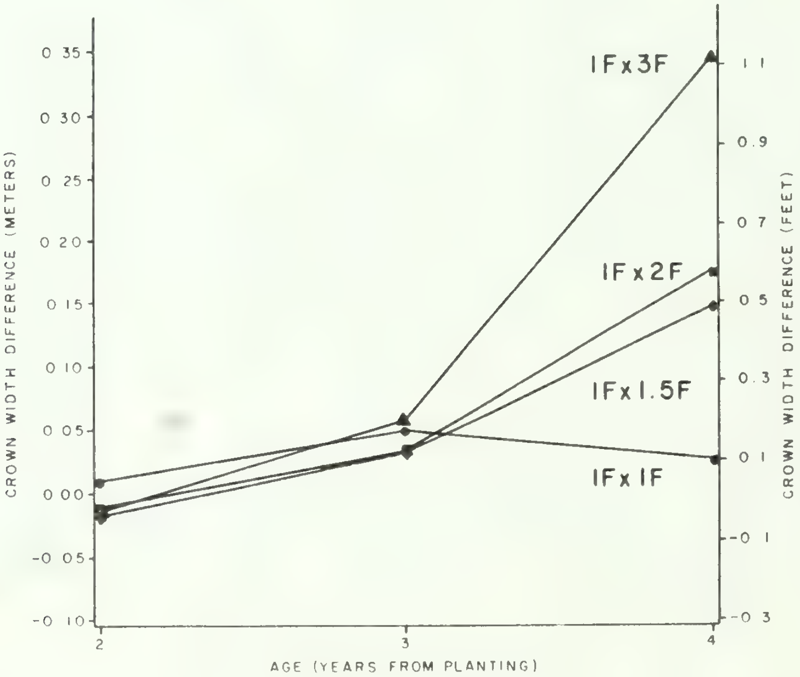

Figure 3. Mean difference between the within-row crown diameter and the between-row crown diameter for the 1F x 1F, 1F x 1.5F, 1F x 2F and 1F x 3F spacings.

likely that the effects of density and spacing would be seen first in the development of crowns for the closer spacings. Therefore, the focus of this section will be on the effects of density and spacing on crown development in the 1F spacings through age four.

Data from the seven 1F spacings (1F x 1F, 1F x 1.5F, 1.5F x 1F, 1F x 2F, 2F x 1F, 1F x 3F, 3F x 1F) in each of the three blocks were used to compute mean crown ratios and crown widths for each of the four different spacings. Thus, means for the 1F x 1F square spacing were computed from three 49-tree plots (one in each block) and means for each of the three rectangular spacings were computed from six 49-tree plots (two in each block). These plots vary in growing space per tree from 16 square feet (1.49 square meters) for the 1F x 1F spacing to 48 square feet (4.47 square meters) for the 1F x 3F spacing. They correspondingly vary in rectangularity from 1:1 for the square spacing to 1:3 for the 1F x 3F spacing.

Figure 2 shows the development of crown ratio from age two to age four for the 1F spacings. From age two to age three, crown ratio increases for each spacing because total height is increasing faster than height to the base of the live crown. However, the rate of increase for the 1F x 1F square spacing is less than any of the rectangular spacings and by age four, it has the smallest crown ratio of any spacing.

The effects of rectangularity on crown development were examined by computing the average between row and within row crown diameter difference for each tree at each of the four 1F spacings. If this difference were zero, then the crown projection for that tree would be circular. The larger the difference, the more elliptical would be the projection. One would expect relatively circular crown projections for square spacings and more elliptical projections as the rectangularity becomes more pronounced. Figure 3 shows that there is little difference between the two crown axes for the square spacing through age four. For the rectangular spacings, however, the difference gets progressively larger from the 1F x 1.5F spacings to the 1F x 3F spacings.

As more data become available, these relationships will be reexamined and a more detailed analysis performed. Data from these spacing trials will provide a continuous source of information with which to better understand the basic relationships that underlie tree growth and stand development.

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DESCRIPTION OF SAMPLING DESIGNS USING A COMPREHENSIVE DATA STRUCTURE

John C. Byrne and Albert R. Stage[1]

ABSTRACT. Maintaining permanent plot data with different sampling designs over long periods within an organization, as well as sharing such information between organizations, requires that common standards be used. A data structure for the description of the sampling design within a stand is proposed. It is based on the definition of subpopulations of trees sampled, the rules used to sample each subpopulation, and linking variables that tie these two elements together. In addition, the data structure includes the spatial relationship of plots within the stand as well as the precision with which tree characteristics are measured. These elements provide all the information necessary for the compilation of stand attributes. Changes in design through the life of a set of permanent plots are common, and the data structure is able to incorporate such changes. The data structure adequately describes an actual, complex subsampling design.

INTRODUCTION

Sharing of data on tree growth between organizations offers many opportunities for improving knowledge of forest yield capabilities. However, common definitions and standards are needed when data from diverse sources are merged. Although standards for measuring trees and describing stand conditions have been established (U.S. Department of Agriculture, 1933; Curtis, 1983), standards for describing underlying sampling designs have been ignored.

Differences in sampling designs may be due to changing objectives and personnel within and between organizations, to changing forest conditions, or to innovation in sampling techniques. Permanent plot catalogs (i.e., COSMADS--Committee on Standards of Measure and Data Sharing; Western Forestry and Conservation Association, 1977) and permanent plot data base systems, including PDMS (Plot Data Management System)[2], have only recently added the capability for describing designs more complex than separate fixed-area plots, such as variable-radius plots or simple cluster and concentric plot designs. Many of the permanent plots that we maintain at the Intermountain Research Station have more complex designs or have had design changes at some time in their life. To incorporate these permanent plots into a shared

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[2] Curtis, R. D., and G. W. Clendenen. 1981. Plot data management system (PDMS) Study Plan. Olympia, WA: U.S. Department of Agriculture, Forest Service, Forestry Sciences Laboratory.

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data base, as well as for ease in compilation of stand attributes, we propose a data structure that can describe a wide variety of designs and changes in design.

ELEMENTS OF DESIGN DESCRIPTION

The objective of this data structure is to facilitate creation of a data set in which each "record" represents an estimate of stand parameters accompanied by treatment, site, and environmental attributes of the stand. The stand represented by the "record" is defined to be an area of ground with relatively uniform conditions that has received a unique treatment combination. In research studies, the experimental unit would correspond to our "stand." This paper will be concerned only with the design characteristics within the stand.

Whereas conventional specification of sampling designs focused on description of "the plot" or "plots" as pieces of ground, the procedure we propose focuses on description of subpopulations of trees and their spatial distribution. The key change in thinking--and in describing the sampling design--is the change from defining the sampling unit as the "plot" drawn from a population of all possible plots in the stand being sampled, to defining the sampling unit as the tree drawn from the population of all trees in the stand being sampled. This concept allows both fixed-area plots and variable probability points to be adequately and similarly described, without resorting to the use of such confusing concepts as "ongrowth" or "offgrowth," that are caused by forcing variable probability points to be described using the "plot" concept.

Designs are characterized by three elements. One element is the spatial layout. This spatial information determines how measurements taken at one place are to be used with measurements taken at a nearby place. The second element describes how different members of the population are to be sampled. For example, the subpopulation of large trees might be sampled on larger plots while small trees might be sampled on one or several smaller plots. The third element describes how tree characteristics are measured for each sampled tree.

SPATIAL RELATIONS

The spatial layout in a stand is described by the numbering scheme of the samples. For finding numbered trees during remeasurement, and for variance calculations, it is essential to know which sample units are nested within sample units used to describe another subpopulation. The fundamental unit in the numbering scheme within the stand is the "plot." A "plot" is defined as the collection of trees included within a single sampling unit. Each plot is given a number. When sampling units are nested, subordinate levels of numbering are needed, i.e., subplots, sub-subplots, etc. Our work with a variety of complex designs suggests that one level subordinate to plot (subplot) would be sufficient for most designs. All sampling units within a nest have the same plot number but different subplot numbers. Once plot and subplot numbers are created, they must never change.

Providing a unique tree identification is an important part of the structure. Each tree is uniquely identified by its plot/subplot/tree number. In repeated sampling of nested plots, trees will often grow from one subpopulation into another subpopulation. Proper compilation of per-acre values requires that a tree growing into a different subpopulation be treated as a new individual in that subpopulation, although identified by its original plot/subplot/tree numbers. A tree can never occur in two or more subpopulations at the same time and can occur only once in each subpopulation.

SAMPLING SUBPOPULATIONS

The totality of trees to be included in stand statistics may be divided into subpopulations. In our data structure each subpopulation must be mutually exclusive and, in the aggregate, encompass the whole population. Each subpopulation is to be sampled with one or more simple sampling procedures. A sampling procedure can be described by the number of samples and the rule that establishes the sampling probability for each individual tree (i.e., plot area for fixed-area plots, basal area factor (BAF) for variable-radii points, etc.). In some cases the stand and plot are synonymous so that all trees in the plot are tallied (and therefore have sampling probability of unity). But in other cases, the stand is too large for complete enumeration and is then sampled with some combination of fixed-area plots, variable-radii points, etc.

In defining each subpopulation, one must record the tree characteristics that are used in delimiting the subpopulation. The most common way of defining tree subpopulations in permanent sample plot work has been by diameter at breast height (DBH) limits. In some studies, the presence or absence of a certain tree characteristic--i.e., whether the tree is alive or dead, the presence of a particular disease organism, etc.--may define the subpopulations. Once the delimiting variable is recorded, the delimiting values of the variable must be entered. For DBH and other continuous variables, the delimiters are the minimum and maximum levels. For discrete variables, codes for specific characteristics are used in the subpopulation definitions. Though in most cases only one variable is used as a delimiter, the data structure is capable of recording several delimiting variables and their chosen values.

The type of sampling rule used to select the trees in each subpopulation defines the probability with which a tree is sampled. For fixed-area samples, the probability of a tree being sampled depends only on its presence or absence. All trees in the defined area that meet the subpopulation definitions are measured, so the sampling probability is proportional to frequency. With geometric point and line sampling, tree size characteristics are used to define the probability of tree selection.

Corresponding to each sampling scheme is an expansion constant used in converting the counts tallied to per-acre stand attributes. For fixed-area plots, the expansion constant is the reciprocal of plot area while for variable-radius points the expansion constant is BAF.

Several examples will help clarify how this expansion constant is used. To calculate trees per acre for a fixed-area plot, the expansion constant is multiplied by the number of trees counted on the plot. But for variable-radius points, the expansion constant is used to calculate a conversion factor for each tree DBH, that is, BAF/(BA for the tree). Then this conversion factor is multiplied by the number of trees counted with that DBH and summed for all DBH classes to get trees per acre.

SUBSAMPLING TREE CHARACTERISTICS

The third element describes the rules specifying which measurements are to be taken on a particular sampled tree. The method we use is to enter values for each tree, however estimated, for each attribute, along with an indicator of their reliability. This indicator, besides noting whether trees were directly measured or estimated, can also describe the general precision associated with each directly measured attribute. The precision will have an impact on how much trust one has in the stand attributes calculated using those measurements. For example, whether heights were measured using a clinometer with ±1 foot precision or using ocular estimation with ±10 foot precision would have an impact on the inferences made from stand attributes based on heights.

LINKING SUBPOPULATIONS TO SAMPLING RULES

To specify compilation procedures to be used at a particular date, it is necessary to link the subpopulation being sampled, the sample rule used, and the date when sampling began to each plot/subplot identifier. Each plot/subplot description includes the total design description of which it is a part. Then, a linking variable in the plot/subplot description references the specific subpopulation that is sampled, the sampling rule, and the date the design was initiated for this plot/subplot. Whenever design changes are made, such as how a subpopulation is sampled, a new set of these linking variables must be added to the description so that analysis procedures can be changed accordingly.

VARIABLES USED IN DESIGN DESCRIPTION

The variables used to describe spatial relations are:

- Plot number
- Subplot number

The variables used to define subpopulations are:

- Subpopulation number
- Variables for delimiting a subpopulation
    - Minimum value or first code for each delimiting variable
    - Maximum value or second code for each delimiting variable

The variables used to describe sampling rules are:

- Sampling rule number
- Variable for defining sampling probability
- Expansion constant
- Number of samples

The linking variables are:

- Subpopulation sampled
- Sampling rule used
- Date design initiated

ILLUSTRATION OF THE DATA STRUCTURE

To demonstrate the capability of the data structure, we will describe an actual sampling design with the design variables. The design we will use for the demonstration is the one used in the Managed Stand Survey in Region 6 of the National Forest Systems (U.S. Department of Agriculture, 1987). A narrative description of this design is: A cluster of five concentric plots is located within a similarly treated area. Each of the concentric plots consist of two plots each: a 1/100-acre plot for counts of live trees <1.0 inches DBH, and a 1/20-acre plot for measurement of live and dead trees ≥1.0 inches DBH. Dead trees are measured as an indicator of wildlife habitat. There is an additional area around the second 1/20-acre plot to record additional live trees with a size of ≥9.0 inches DBH. Fewer characteristics are measured on the trees in this area than on those similarly sized trees in the 1/20-acre plot. The area of this plot is 3/20 acre, the "donut-shaped" area between a 1/5-acre plot and a 1/20-acre circular plot. Figure 1 is a schematic drawing of this design for one stand.

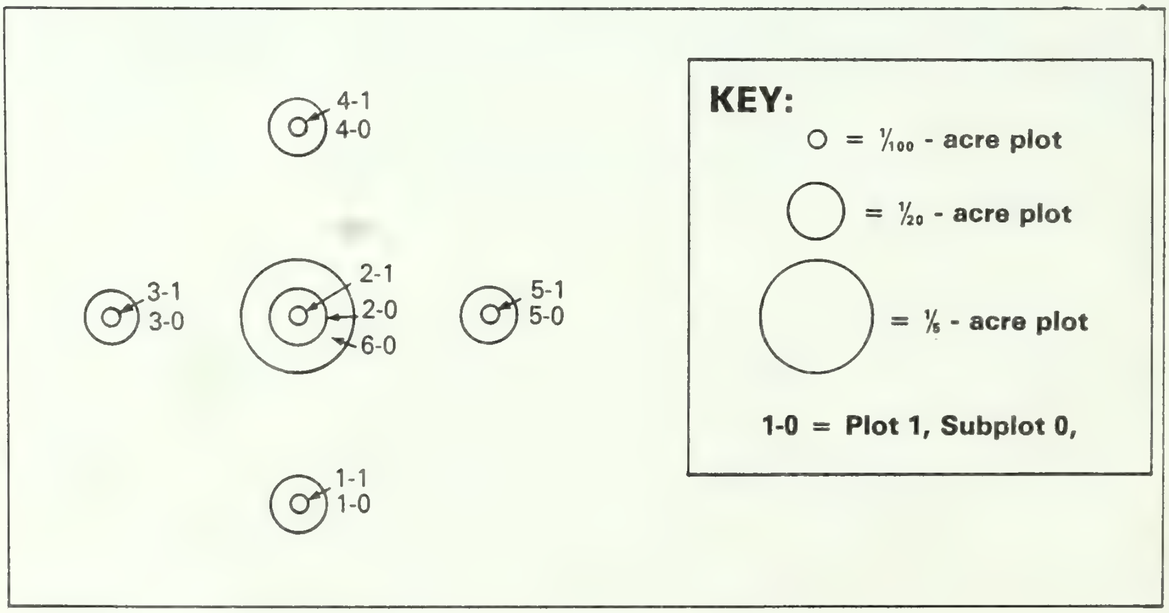

Figure 1. Schematic drawing of example design.

There are four separate subpopulations represented in this design. They are defined in Table 1.

TABLE 1. Definition of subpopulations for example design.

Subpopulation Number	1	2	3	4
1st variable for subpopulation definition	DBH	DBH	DBH	DBH
Minimum or 1st code	9.0"	9.0"	1.0"	0.0"
Maximum or 2nd code	99.9"	99.9"	8.9"	0.9"
2nd variable for subpopulation definition		TC	TC	
Minimum or 1st code		2	0	
Maximum or 2nd code			2	

TC = Tree class, where 0 represents live trees and
2 represents dead trees.
Tree class codes used as subpopulation defining variables only when codes other than live are used.

Three sampling rules are represented in the design and are described in Table 2.

TABLE 2. Definition of sampling rules for example design.

Sampling rule number	1	2	3
Variable defining probability	FQ	FQ	FQ
Expansion constant	20	6.667	100
Number of samples	5	1	5

FQ = Frequency

And finally, the numbering scheme for the plots and subplots within the design is shown. A linking variable, included with the numbering, links the numbering scheme to the sampling design description (i.e., 2-1-1987 means subpopulation 2 is sampled using sampling rule 1 beginning in 1987).

TABLE 3. Numbering scheme and associated linking variables for example design.

Plot number	Subplot number	Linking variables
1	0	1-1-1987, 2-1-1987, 3-1-1987
1	1	4-3-1987
2	0	1-1-1987, 2-1-1987, 3-1-1987
2	1	4-3-1987
3	0	1-1-1987, 2-1-1987, 3-1-1987
3	1	4-3-1987
4	0	1-1-1987, 2-1-1987, 3-1-1987
4	1	4-3-1987
5	0	1-1-1987, 2-1-1987, 3-1-1987
5	1	4-3-1987
6	0	1-2-1987

In compiling stand attributes using this design, several things must be considered. First, because the stand is subsampled it is possible to calculate a variance estimate for each attribute of interest, but the covariance between the plots in each nest must be included in the overall variance estimate. And second, instead of calculating the contribution of each plot to the stand attribute estimate, it may be better to calculate the contribution of each subpopulation because trees in the nested plots will move from one subpopulation to another.

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THE PACIFIC NORTHWEST STAND MANAGEMENT COOPERATIVE AND ITS FIELD INSTALLATION DESIGN

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ABSTRACT. The Stand Management Cooperative is a joint effort of twenty-two organizations in the coastal Pacific Northwest to meet data needs for construction of growth models. The data base will be specifically applicable to young stands, many of them plantations. The Cooperative addresses both the conventional measures of response to silvicultural treatment and the effects of treatment on wood quality. Data will be used to develop models to guide management of large areas of young stands by providing better estimates of the consequences of alternative management regimes. Cooperative objectives and standard designs adopted by the Cooperative for permanent plot installations are described.

INTRODUCTION

Over the years many organizations have established permanent plot experiments in Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) and western hemlock (Tsuga heterophylla [Raf.] Sarg.) forest types in the coastal Pacific Northwest. During the past decade there have been a number of efforts to bring this information together for silvicultural interpretations and construction of growth and yield projection systems. These efforts revealed several problems, including data incompatibility and the realization that although considerable permanent plot data exist for these types, relatively little of it is applicable to the stand conditions we expect in the future.

Starting about 1982, a number of organizations began joint discussions concerning possible cooperative efforts to develop needed data. Several working groups reviewed the situation and confirmed the need for high-quality, consistent, and compatible data on (1) effects of early density control, specifically including very wide spacings, (2) effects of later silvicultural treatments applied to stands that have had such early density control, and (3) effects of early density control and later silvicultural treatments on wood properties and value.

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Current thinking in the region favors much wider spacings than have been common in the past. We lack information on the response of such stands to treatment. Of particular concern is the lack of specific quantitative information on the effects of such regimes on wood quality, although the information available suggests that wood quality may be the major factor determining acceptable management regimes. These discussions led to formal establishment of the Stand Management Cooperative in January 1985.

THE STAND MANAGEMENT COOPERATIVE

The purpose of the Stand Management Cooperative is to provide a continuing source of high-quality data on the long-term effects of silvicultural treatments and treatment regimes on stand and tree development and wood quality. The integrated program aims to quantitatively define effects of treatments on growth, yield, and wood properties, and to forecast more accurately the consequences of alternative management regimes.

Cooperative activities are restricted to two species, Douglas-fir and western hemlock, in the coastal Douglas-fir region of Oregon, Washington, and British Columbia. Other species will be included in the future if there is sufficient cooperator interest. Plots will be established in planted stands or stands with early density control, over a wide range of site conditions and geographic areas.

The Stand Management Cooperative currently comprises twenty-two member organizations (Table 1). Sixteen contributing member organizations representing forest industry and federal, provincial, and state agencies provide support and direction for the project. Six institutional members participate in the Cooperative, furnishing technical expertise and research support. The University of Washington serves as Cooperative headquarters and provides program administration and staffing.

Table 1. Member organizations of the Stand Management Cooperative. Institutional members marked with "*".

Bohemia, Inc.
British Columbia Ministry of Forests and Lands
Cavenham Forest Industries
Champion International Corp.
Forintek Canada Corporation *
Georgia-Pacific Corporation
International Paper Company
Longview Fibre Company
MacMillan Bloedel Ltd.
Municipality of Metropolitan Seattle (METRO)
Oregon State University *
Port Blakely Tree Farms
Simpson Timber Company
University of British Columbia*
University of California, Berkeley *
University of Washington *
USDA Forest Service
USDI Bureau of Land Management
Washington Department of Natural Resources
Washington State University *
Weyerhaeuser Company
Willamette Industries

The Cooperative includes two projects: Silviculture and Wood Quality. Project Leaders are supported by Technical Advisory Committees composed of individuals from member organizations with specific skills and interests. Program and study plans are prepared jointly by the Project Leaders and Technical Advisory Committees. A Policy Committee representing all members meets annually to review plans and accomplishments and approve work plans and budget. Overall program coordination is provided by the Director, working closely with the Project Leaders and the Policy Committee Chairman.

Field work and data management are administered by the University of Washington. Member organizations have the option of providing personnel to do the field work, under supervision from the Cooperative, with an appropriate credit against contributions to the Cooperative. Thinning and other treatments are applied by the landowner to Cooperative specifications.

SILVICULTURE PROJECT FIELD INSTALLATIONS

Development of the field installation program began with a number of assumptions and requirements that influenced experimental design:

1. Primary interest is in inferences and predictions applicable over the region. Therefore, installations should sample the range of sites and physiographic conditions within the coastal Douglas-fir region.

2. Installations should be designed so that they can be continued beyond currently accepted rotation age.

3. Plots should be large enough so that (a) number of trees is sufficient for reasonable estimates of diameter distributions, (b) number of trees will allow reasonable thinning, (c) death of individual trees or small groups of trees will not greatly influence plot values, and (d) plot values can be considered a reasonable approximation of results attainable on an area of operationally treatable size.

4. The design should be such that it is not unduly difficult to find suitable areas.

The primary aim is to obtain data suitable for fitting regionally applicable response surfaces, rather than to test statistical significance of differences at individual locations. The need for relatively large plots, combined with the limited size of areas acceptably uniform in site and stand conditions, makes replication at individual locations impractical. Therefore, one replicate of the chosen set of treatments is established at each location, with the closest feasible consistency in site and initial stand conditions among plots at a location.

Three types of field installations are being established, designated Types I, II, and III. The Type I is the basic or "core" installation; Type II is a simplified analog established in somewhat older stands; and Type III is an effort to provide research and demonstration areas for the future.

TYPE I INSTALLATIONS

The primary objectives of Type I installations are (1) to provide data to assess the effects of wide early spacing on subsequent tree and stand growth, yield, and wood properties and value, and (2) to provide data to assess the effects of later thinning, applied to stands having early stocking control, on subsequent tree and stand growth, yield, and wood properties and value. Secondary objectives are to assess the effects, in combination with early spacing and later density control, of pruning, tree selection during precommercial thinning, and fertilization.

Installations are established in uniformly stocked plantations (or recently respaced natural stands) on acceptably uniform sites. Present number of stems should be in the range of 300 to 680 per acre.

The desired initial densities are achieved through systematic respacing of existing stands rather than through planting bare ground. This will reduce the time necessary to obtain preliminary results and will avoid early establishment and survival problems. Respacing must be done before the onset of substantial competition.

Treatments

Respacing--Three initial densities are used in each installation. These are not necessarily the same at all installations. The initial stems per acre (ISPA) are reduced by one-half and one-fourth by systematic removal of the corresponding fraction of trees. These treatments will produce a range in density from about 75 to 680 stems per acre. No effort is made to specify the exact number to be left in an installation, but the procedure ensures that a wide range of SPA is represented. The intent is to create "pseudo plantations" that simulate plantations established with initial numbers of stems ISPA, ISPA/2, and ISPA/4.

Thinning--Later thinnings are superimposed on the ISPA and ISPA/2 spacings (Table 2). The intent is to include a minimum number of strongly contrasting regimes that appear appropriate to the stand conditions and some plausible set of owner objectives.

Supplemental treatments--a subset of installations will have additional plots with supplemental treatments of pruning, selective versus systematic leave tree selection, and fertilization.

Field Layout

The basic plot design consists of a square 0.5 acre measurement plot surrounded by a 30.5 foot buffer. A double buffer is provided on one side of the plot to allow for future destructive sampling, giving a total treatment area of 1.14 acres. (Supplemental pruning plots are one-half this size.) Plots are located within the study area so as to minimize between-plot variation, then treatments are randomly assigned to plots.

Table 2. Density control treatments for Douglas-fir and western hemlock Type I installations.

SPA[a]	Treatment[b]	Density control regime[c]
ISPA/4	1	No thinning.
ISPA/2	2	Minimal thinning: thin at RD55 to RD35; no further treatment.
	3	No thinning.
ISPA	4	Repeated thinning: thin at RD55 to RD40; second thinning at RD55 to RD40; subsequent thinnings at RD60 to RD40.
	5	Minimal thinning: thin at RD55 to RD35; no further treatment.
	6	No thinning.
	7	Reserved. (Thinning regime to be defined)

[a] ISPA = numbers of stems per acre at time of installation establishment

[b] Supplemental treatments of pruning, selective versus systematic leave tree selection, and fertilization will be included in a subset of installations for a maximum of 15 plots.

[c] Stand density given in terms of relative density (RD) (Curtis 1982), defined as (basal area)/(average DBH)$^{0.5}$. A numerical value of RD=70 (RD70) corresponds approximately to "normal" stand density in yield tables such as McArdle et al. (1961) and Curtis et al. (1982).

Measurements at time of plot establishment for all trees include diameter at breast height, age at breast height, total height, height to live crown base, and evaluation of tree vigor. Measurements are taken on the 0.5 acre measurement plot only. Planned measurement interval is four years.

Our goal is to establish 24 Douglas-fir installations and 8 western hemlock installations by 1990. Installations would be distributed over the range of site classes (I-V) and physiographic regions defined within the geographic scope of the Cooperative.

TYPE II INSTALLATIONS

Information on density control effects in planted stands of commercial thinning size will not be available from Type I installations for at least 15 years. Meanwhile, many planted stands will have reached commercial thinning size. Currently, little information exists on results of commercial thinning applied to these conditions.

A limited number of installations, designated Type II, will be established in existing plantations that are now approaching commercial thinning stage. Objectives are (1) to provide partial results in the near future for a subset of the thinning treatments in the Type I installations, and (2) to provide experience in choosing, defining, applying, and controlling treatment regimes that will be applicable to the basic Type I installations when they reach a comparable stage. The preliminary results from the first objective are particularly critical given the large area of plantations now approaching commercial thinning stage.

Type II installations are established only in Douglas-fir plantations or respaced natural stands. Present SPA is expected to be 200 to 450 per acre, with most probably in the range of 300 to 450. Average diameter should be about 6 to 10 inches, with present RD (Curtis 1982) less than 55.

Treatments

The density control treatments for Type II installations are shown in Table 3. Treatments 1, 3, and 5 correspond to treatments 4, 5, and 6 in Type I installations (Table 2). Treatment 2 provides a contrasting density level for repeated thinning; while treatment 4 provides information on effect of delaying thinning. No supplementary treatments are included. Field layout and measurement schedules are the same as for Type I installations.

Table 3. Density control treatments for Type II installations.

Treatment	Density control regime
1	Repeated thinning, high density regime: first thinning at RD55 to RD35; second thinning at RD55 to RD40; subsequent thinnings at RD60 to RD40.
2	Repeated thinning, low density regime: first thinning at RD55 to RD30; subsequent thinnings at RD50 to RD30.
3	Minimal thinning: thin at RD55 to RD30; no further treatment.
4	Delayed thinning: Thin at RD65 to RD35; no further treatment.
5	No thinning.

Our goal is to establish 12 installations in Douglas-fir stands by 1990. Because of the small number of installations planned, establishment will be confined to site classes II, III, and IV (95 ft. < site index <135 ft.; base age 50 years).

TYPE III INSTALLATIONS

Installations designated Type III are being established to provide for future studies. These installations will be in areas scheduled for operational planting and will include six standard initial spacing levels. Plantation establishment should use the best available technology so that future development of these plantations will be representative of the best practices available today.

The objectives of Type III installations are (1) to provide plantations suitable for future installation of research studies, (2) to provide areas for future destructive testing of wood grown in stands with a wide range of stand densities, (3) to provide an opportunity to assess results of the best stand establishment practices currently available, and (4) to provide relatively large areas for visual demonstration of spacing effects.

Treatments

Each installation is planted at six different initial spacing levels. Target densities are approximately 100, 200, 300, 440, 680, and 1,210 stems per acre, corresponding to average nominal spacings of 21x21, 15x15, 12x12, 10x10, 8x8, and 6x6 feet.

Field Layout

Three kinds of Type III installations are planned: (1) pure Douglas-fir, (2) pure western hemlock, and (3) a 50:50 mix of Douglas-fir and western hemlock. We hope to establish an approximately equal number of installations in each category, although operational realities will probably weight the total toward Douglas-fir.

The available area is subdivided into blocks of at least three acres each in any convenient way that will provide easily relocatable boundaries and minimum variation in site quality. Spacing levels are then randomly allocated among the blocks.

Planting follows normal operational practice except for the differences in spacing. The average number of trees per acre (average SPA = 488) differs little from common operational practice. The only additional costs are those incurred in area selection and in marking the areas to be planted at different spacings.

GOALS AND STATUS

The goals mentioned previously sum to the following:

Type I installations: 32 installations with more than 300 plots in Douglas-fir and western hemlock stands.

Type II installations: 12 installations with 60 plots in Douglas-fir stands.

Type III installations: a minimum of 15 installations planted as pure and mixed stands of Douglas-fir and western hemlock.

These experiments are planned for a duration of about 50 years for Types I and III, and 30 years for Type II. We do not expect that all will survive accidents or changes in ownership.

During 1986 we prepared and tested a manual of standardized field procedures and developed the framework for a data base management system. Prototypes of Type I (2 installations), Type II (2 installations), and Type III (4 installations) were established. Installation establishment on a production basis is under way in 1987, with the aim of reaching our planned number of installations in a five-year period.

CONCLUSIONS

We believe that cooperative efforts such as the Stand Management Cooperative are the most promising means--and perhaps the only feasible means--for providing a continuing source of high-quality treatment response data. These data are needed for construction of reliable models that can guide owners in evaluating alternative management regimes. The costs to an individual owner are far less than those of an independent effort, and the range in both the conditions represented and the expected sample size is far greater. Response from the region's land-managing organizations has been most gratifying.

The Stand Management Cooperative is perhaps unique in giving emphasis to treatment effects on wood and product quality, which we think is likely to be as important to our future regional competitive position as is volume production. We also believe the installation design will overcome some of the difficulties that have plagued past long-term studies of silvicultural regimes in the Pacific Northwest.

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A REPORT ON THE PERMANENT PLOT TASK FORCE

Robert O. Curtis[1]

ABSTRACT. A task force on permanent plot standards has reviewed problems and needs within the USDA Forest Service and has recommended ways to improve programs and the quality and consistency of data used for growth and yield systems. Its recommendations are now being implemented.

INTRODUCTION

In recent years, the Forest Service has become increasingly aware of the need to develop growth and yield systems to meet the needs of the National Forests. A 1983 in-Service report listed a series of problems perceived as obstacles to such development within the Forest Service.

One obstacle was "the lack of quantitative growth and yield data over broad geographic regions and for an array of forest types, which often limits research, development, and implementation."

Regions and Stations were asked to prepare joint growth and yield action plans; and to review the needs, information available, and future plans for their respective areas. These plans were summarized in a 1985 in-Service report that listed issues and recommended several actions at the national level. Among these were the statements (1) that "the lack of quantitative data bases is the primary limitation to development and implementation of models," and (2) that there is a need for "provision for establishment and maintenance of permanent growth and yield plots on National Forest lands," which will "require a well planned long-term data collection and analysis commitment...." One of several specific recommendations was that the Chief establish a task force including Timber Management Research, Timber Management, Forest Inventory and Analysis, and Land Management Planning to develop standards for

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establishing permanent plots on National Forest lands to serve growth and yield research, forest inventory and survey, and monitoring of forest plans.

This task force was established in early 1986 and consisted of Dwane Van Hooser, Jim Brickell, Gyde Lund, Neil Lamson, Bob Bailey, and me as chairman. I will summarize the main points in our report. Though it may include some things peculiar to the Forest Service, I think many of you will recognize our problems in your own organizations.

OBJECTIVES

Our instructions were "to develop standards for establishment of permanent plots...." We took this to include the uses of permanent plots, factors affecting their design and measurement, and practical questions dealing with organization and objectives, in addition to measurement procedures. We understood our assignment to refer only to permanent plots that involve measurement of timber. We did not think we could or should specify procedures for the entire country in great detail, and much of our report is a discussion of principles and past experience that should guide any permanent plot program.

USES OF PERMANENT PLOTS

Permanent plots have two main uses, to measure change and to determine how change is influenced by stand attributes and stand treatment.

Two goals can be distinguished (Curtis and Hyink, 1985): to estimate the current "growth trend" of the existing forest and to estimate "response to treatment."

These goals are not the same, and they generally cannot be met from the same data. The different objectives of inventory, monitoring, and research lead to different plot designs and different sampling designs.

Inventory and monitoring plots represent the growth of the present forest, which is the result of past actions and past conditions. For answers to "what if" questions, such as choices among alternative treatments and management regimes, or forecasts of the results of stand treatments different from those that produced the present forest, we need data from research plots that are designed to provide response data for a wide range of initial conditions and stand treatments.

Growth and yield systems intended to answer the "what if" questions must rely primarily on research data. Suitable inventory and monitoring plots can provide useful supplemental information for system construction and are necessary for system calibration, evaluation, and application. Definitions and measurement standards must be consistent for both types of data. We must measure the same variables by consistent procedures.

Our report included an extended discussion of designs and recommended a minimum set of measurements that should be routine on all permanent plots that may be used either for system development or as input to system applications. I am not going to go through these, but I will mention some past difficulties that have repeatedly been encountered.

PAST PROBLEMS, NEEDS, AND OPPORTUNITIES

DESIGN AND MEASUREMENT

Historically, permanent plots have been established by individual scientists and local work units, for a variety of purposes. They have often been useful for purposes other than those originally intended. Design and measurement procedures have generally been determined by the individual or unit. These individuals and units have differed widely in knowledge, experience, and objectives and have had similar difficulties and made similar mistakes. Inventory plots have perhaps been more standardized, but designs and standards have changed repeatedly and differ among administrative units.

The result is inconsistency between data sets. Measurements present in one set are lacking in another or were taken to different standards not easily convertible to a common basis. Difficulties are often compounded by poor documentation and by differences in data codes and formats. Screening data and trying to reconcile data from different sources can be an almost endless task, and one that makes up a substantial part of the total cost of system development.

Additional problems occur repeatedly in much existing data and severely reduce or destroy their value. These include such things as small plots with large edge effects, ages recorded by broad classes, poor height samples and sloppy height measurements, omission of small trees, and so on.

As an example, one may get data for a set of plots that include stand age. Is this age at breast height? Total age? An age determined by boring? Years since planting? Is it an actual average of measured values, or merely a broad class value? If it is a mean of measured values, is it based on all tree classes? Dominants only? Or what? On inquiry, one may discover that the only person who knows retired last year and moved to Florida. The list is endless.

Permanent plots are expensive, and we cannot afford to have individuals doing their own thing and repeating past mistakes. New permanent plots generally should be established only as part of a carefully planned and thoroughly reviewed program. We need minimum standard procedures that are routinely followed. These procedures need to recognize differences in objectives, but they should provide for compatible procedures and compatible measurements on a common set of basic variables.

DATA MANAGEMENT

Database management and data summarization have been continuing sources of major costs and frustrations to all who attempt to use or recover available information. This is particularly true if the data come from a source over which the current user has no control.

Any system of permanent plots generates huge amounts of data that must be entered, edited, updated, and summarized in a variety of ways. We have universally underestimated the time and cost and the expertise required.

The Forest Service has no standard and generally applicable programs for performing these tasks. Each unit has developed its own procedures and programs. Unit capabilities vary widely, and people often are unaware of what others have already done. The result has been a large and redundant expenditure of resources on program development, and we still did not have widely available, efficient, consistent, easy-to-use standard programs.

QUALITY CONTROL

Tight quality control is an essential part of any permanent plot program. This requires (1) defined measurement standards and procedures, (2) field checks, (3) adequate data editing procedures, and (4) specialized personnel with adequate supervision.

Plot establishment and remeasurement must be supervised by competent people for whom this is a major duty. Personnel on Forest Service Ranger Districts who spend only a small part of their time on this activity cannot be expected to have the needed expertise.

COORDINATION BETWEEN THE NATIONAL FOREST SYSTEM (NFS) AND RESEARCH

Research staff working in growth and yield and NFS staff concerned with inventory and management planning have often lacked communication and common understanding. Many researchers lack familiarity with current inventory procedures and existing inventory data. Often they know little about the planning process and its information needs.

Conversely, they have had little opportunity to influence inventory and monitoring procedures to make such data more useful and more compatible with research-developed growth and yield information. There is a need to promote dialogue and common understanding.

Much of the existing research permanent plot data is the product of informal cooperation between NFS and Research. But there has rarely been a comprehensive program to establish permanent plots to a consistent design over a region or type, specifically to meet the needs of growth and yield system development. We need such programs.

Permanent plots for monitoring "growth trends" in operationally managed stands are logically part of the inventory system. But "treatment response" studies are also necessary, and they require a series of installations across the range of site conditions and possible treatments. These installations could be installed and maintained as a joint effort of Stations and Regions. Objectives and plans should be developed jointly by Stations and Regions, with Stations having primary responsibility for design and data analysis, and NFS much of the responsibility for maintenance and treatment applications.

COOPERATION WITH OTHER OWNERS

National Forest planning inventories and forest plan monitoring are by their nature specific to National Forest ownership.

This is not true of data used for model development and for evaluation of treatment response and silvicultural alternatives. Species do not change their characteristics across a property line. Data from similar lands in other ownerships are equally applicable and are often essential for broadening the range of combinations of sites, age classes, and treatments represented.

We in the Forest Service should not be thinking of plots on National Forest lands as the only source--or even the primary source--of treatment response information and data for model development. Carefully planned cooperative programs that include other owners and other users of permanent plot data provide major opportunities for savings in time and money and enhanced program effectiveness. These programs can benefit all parties.

Cooperatives can be used to both plan and install permanent plots, and for pooling and analyzing data. The leverage they provide makes possible much more extensive programs than would be possible for either the Forest Service or any other organization acting independently. Cooperatives also help to preserve program continuity and to promote the use of compatible and consistent data collection procedures.

Successful cooperative programs require careful planning and long-term commitment. The Forest Service must be actively involved in program planning and in subsequent implementation and data analyses to ensure that program direction remains consistent with Forest Service needs. Paying the dues and attending the annual briefing are not enough.

Cooperatives are often the most promising and most cost-effective means for developing the treatment response information needed for system development. They may be the only means feasible under prospective personnel and funding constraints. The costs will be far less than those of any attempt to go it alone.

CONTINUITY AND FUNDING

Any program to develop the needed data bases will require continuity in programs, procedures, and personnel.

Most of our present knowledge and our data bases for growth and yield work are the product of the past efforts of a few farsighted and dedicated individuals. Permanent plot programs that depend on the support and interest of a particular individual are highly vulnerable to personnel changes, and managers are constantly tempted to sacrifice long-term goals to immediate competing needs.

TASK FORCE RECOMMENDATIONS

The Task Force made several specific recommendations in its report, which I have condensed here:

1. Continuity in programs, procedures, and personnel are essential. There should be:

- clear policy direction emphasizing long-term commitment, with attendant guidelines; and
- a funding mechanism that specifically allocates funds to these activities, rather than leaving allocation to the local managers' discretion.

2. Measurements taken and procedures used in inventories, monitoring, and stand examinations should be compatible with those used in treatment response studies. The same basic variables should be measured in a similar manner, as specified in the manuals proposed in our report.

3. The Forest Service should adopt a nationwide standard minimum set of core variables to be used on all permanent plots that include measurement of timber.

There is need for:

- national manual direction documenting the core requirements for permanent plot procedures and measurements; and
- Region and Station handbooks documenting Region and Station standard procedures, including but not limited to the standard minimum set of variables. These should be subject to Washington Office review and approval.

Where feasible and appropriate, definitions, standards, and recommendations in the Task Force report should be incorporated in the new "Resource Inventory Handbook" (discussed by Lund, in press), now in preparation.

4. Several research scientists with growth and yield backgrounds should be added to the working group preparing the Forest Service "Resource Inventory Handbook" (1) to promote consistency and compatibility between research definitions and needs and those used by NFS and Forest Inventory and Analysis, and (2) to ensure that guidelines for monitoring are based on a common understanding of definitions and objectives and will produce data compatible with prospective growth and yield system needs.

5. The Forest Service should have standard computer programs for database management and permanent plot data summarization, with versions suitable for use on microcomputers and on its Data General minicomputers.

Programs and procedures now in use should be surveyed to identify (1) the systems best suited to general use; (2) further development needed to produce generally applicable systems; and (3) documentation, training, and support needed to make these systems widely available.

6. Within each Region in the National Forest System, the primary responsibility for training, quality control, manual development, and so forth, should be given to one person with expertise in this area.

Responsibility for plot installation and maintenance should be at the Forest level rather than at the District level, with technical coordination and data management at the Region and Station level.

7. Policy direction and funding procedures should specifically encourage cooperative arrangements with other land management and research organizations for collecting, sharing, and analyzing data. The Forest Service should be active in the planning and operation of such cooperatives.

IMPLEMENTATION

The Task Force recommendations have been accepted in principle, and measures to implement them are now in progress. Only time will tell the extent of the changes, but we feel that the Task Force has clarified the problems and pointed the organization toward better coordination and more effective work in this area. The Task Force has certainly been a valuable educational experience for its members.

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MONITORING LAND/FOREST COVER USING THE KALMAN FILTER: A PROPOSAL

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ABSTRACT. Although growth and yield models have been used to update forest inventories for large regions, such models poorly predict cover changes from land use conversions, regeneration, and harvest. These changes could be monitored directly for large areas using remote sensing, which can be expensive, or estimates made by agricultural agencies, which are not detailed for condition of timberlands. The Kalman filter, which is a flexible statistical estimator, might increase statistical efficiency and produce annual estimates of cover by combining such direct monitoring with past knowledge (i.e., previous forest inventory) and expected change (i.e., model for annual change in land cover). This paper describes a potentially useful application of this topical estimator and presents specific proposals for practical methods.

INTRODUCTION

Inventories performed by the USDA Forest Service, Forest Inventory and Analysis (FIA) Projects (Cost and Knight, 1983; Frayer and Beltz, 1986) are adequate for their intended applications but are 1 to 10 years old. Models have been used to update (Smith and Hahn 1986) and reduce cost (MacLean 1981) of FIA inventories. However, most models do not predict changes in area caused by harvesting, regeneration, and conversions in land use. This paper describes the Kalman filter, and discusses how it might be used to monitor land cover-ownership (Table 1). The Kalman filter includes a deterministic model for change in a multivariate system over time, and a measurement model for a time series of monitoring data. Estimates from the most current FIA inventory could serve as initial conditions (i.e., time t=0). Subsequently (t>0), remotely sensed data and areal estimates of cover from other agencies would serve as monitoring data. Areal models of annual change in land cover, possibly based on econometric methods, would be used in the Kalman filter to combine this time series of data into a single, dynamic estimator. However, estimation errors would eventually build to unacceptable levels, and a new FIA inventory using traditional methods would be required. Until then, efficient annual estimates of cover would be produced for resource planning at the Federal and State levels.

KALMAN FILTER

The Kalman filter (Kalman 1960) was originally developed for aerospace control problems. Its derivation is given by Lee (1964); Jazwinski (1970), Harrison and Stevens (1976), Maybeck (1979), and Sorenson (1985) provide contemporary descriptions. Dixon and Howitt (1979) proposed it for continuous forest inventory, and Visser (1986) and VanDeussen (1987) have used it in dendro-ecological studies. It is a vector analog of the familiar estimator used

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TABLE 1. Land classification system

Land Ownership	Land Cover	Forest Condition	
PUBLIC (censused)	FOREST	FOREST TYPE	SIZE CLASS
National Forest	Timberland	Pine	Sawtimber
Other federal	Woodland	Oak-pine	Poletimber
BLM		Upland hardwood	Seedling-sapling
Indian		Bottomland hardwood	Nonstocked
Misc. Federal			
State			ORIGIN
County & Municipal			
FOREST INDUSTRY (censused)			Natural
			Planted
Owned	NONFOREST		
Leased	Cropland		
PRIVATE (not censused)	Grassland		
	Barrenland		
Farmer	Urban		
Other private	Water		
Other corporate			

in sampling with partial replacement, in which components are weighted in inverse proportion to their variances (Gregoire, personal communications).

The Kalman filter is given by model (1), which represents the linear change ($\underline{\Phi}_t$) in a multivariate system ($\underline{x}$) between time t-1 and t, and model (2), which describes the linear relationship ($\underline{H}_t$) between measurements of the system ($\underline{y}_t$) and the true, but unknown state of the system ($\underline{x}_t$).

$$\underline{x}_t = \underline{\Phi}_t \, \underline{x}_{t-1} + \underline{w}_t \qquad (1)$$

$$\underline{y}_t = \underline{H}_t \, \underline{x}_t + \underline{v}_t \qquad (2)$$

$\underline{y}_t$ can represent a time series of vectors for independent sources of measurement data. The vector of prediction errors $\underline{w}_t$ has a zero mean vector and covariance matrix $\underline{Q}_t$. The vector of measurement errors $\underline{v}_t$ has a zero mean vector and covariance matrix $\underline{R}_t$. $\underline{w}_t$ and $\underline{v}_t$ are vectors of random variables; their exact values are unknown, but estimates can be made for $\underline{Q}_t$ and $\underline{R}_t$, and assumptions made regarding their true distributions.

The state vector ($\underline{x}_t$) might represent hectares in each of n land/forest cover categories (Table 1) at time t. The true, but unknown, state vector ($\underline{x}_t$) equals an estimated state at time t ($\hat{\underline{x}}_t$) plus a vector of estimation errors ($\underline{\epsilon}_t$).

$$\underline{x}_t = \hat{\underline{x}}_t + \underline{\epsilon}_t$$

$\underline{\epsilon}_t$ has a zero expected value and covariance matrix $\underline{P}_t$. If error vectors $\underline{w}_t$, $\underline{v}_t$ and $\underline{\epsilon}_0$ are multivariate normal for all values of t, then $\underline{\epsilon}_t$ will be multivariate normal, and confidence intervals for $\underline{x}_t$ are readily computed using $\underline{P}_t$.

The state vector at time t is estimated using the state vector at a prior time (t-1) and expected change between t-1 and t

$$\hat{\underline{x}}_t = \Phi_t \, \hat{\underline{x}}_{t-1} \tag{4}$$

The covariance matrix for propagated estimation errors ($\underline{P}_t$) is a function of the previous covariance matrix for estimation errors at time *t*-1 ($\underline{P}_{t-1}$), the expected change in the state of the system (Φ_t) from model 1, and the covariance matrix for prediction errors between *t* and *t*-1 ($\underline{Q}_t$).

$$\underline{P}_t = \Phi_t \, \underline{P}_{t-1} \, \Phi_t^T + \underline{Q}_t . \tag{5}$$

This requires estimates of initial conditions $\underline{x}_0$ and $\underline{P}_0$.

Measurements at time *t* can improve the updated estimate. Measurements might be estimates of hectares in *m* land/forest cover types from remote sensing or from other agencies. The composite estimator, which combines prior knowledge (model 1) with a new vector of measurements (model 2), is

$$\hat{\underline{x}}_t^* = [\underline{I} - \underline{G}_t \, \underline{H}_t] \, \hat{\underline{x}}_t + \underline{G}_t \, \underline{y}_t , \tag{6}$$

where $\underline{G}_t$ is computed to produce the minimum variance estimate (see Appendix).

This estimator has less variance in estimation error ($\underline{P}_t^*$) than the prior estimate ($\underline{P}_t$) because

$$\underline{P}_t^* = \underline{P}_t \, (\underline{I} - \underline{G}_t \, \underline{H}_t), \tag{7}$$

where ($\underline{G}_t \, \underline{H}_t$) has values from zero to one.

FIA DATA

FIA units provide the most detailed, reliable, statistical estimates of forest cover for the entire United States. Every 5 to 10 years, areal estimates are made for condition of forestland in multi-county physiographic regions (i.e., Inventory Units) in each State. The following describes FIA methods used in the southeastern United States, with specific examples from the 1984 inventory of North Carolina (NC) from Sheffield and Knight (1986).

First, complete aerial photo coverage is used to estimate area of timberland in each county; it is 1:40,000-scale black and white, or 1:58,000-scale color infrared (CIR) prints, and can be up to 10 years old. Temporary plots, nominally 12 ha, are systematically located on the photographs, and the proportion of timberland for each plot is photointerpreted. There were 91,765 photo samples (1 per 138 ha) in the 1984 inventory for NC. Photointerpretation is verified on the ground for a subsample (e.g., 8,123 out of 91,765 photo samples in NC). Estimates of total timberland are adjusted for misinterpretations and changes since the date of photography using double sampling with regression.

Second, exact area of timberland for certain ownerships (Table 1) is censused for each county using information from forest-product industries and government agencies. It is impractical to census area of other timberlands managed by non-industrial, private forest (NIPF) landowners (typically 75% of the timberland in the Southeast). Third, permanent ground plots, nominally 0.4-ha, are systematically installed in timberland by field crews (5,355 plots in 1984 for NC). Field crews remeasure forested permanent plots (4,878 of the 5,355 in NC) for estimates of growth, removals, and mortality. Ground data are used to classify each plot using the system in Table 1. In addition, a few temporary

0.4-ha ownership plots are measured by field crews to describe area in ownerships that do not contain a permanent ground plot in a county. This procedure produces reliable estimates of area for classes in Table 1 within each Inventory Unit.

REMOTELY SENSED DATA

The following assessment of remote sensing strategies for the southern United States is based on Catts et al. (1987) and Czaplewski et al. (1987). It emphasizes statistical estimates for large regions rather than in-place vegetation maps required for land management or extension efforts. Three sources are considered: digital satellite data, high-altitude aerial photography, and medium- or large-scale aerial photography.

Forest type and some classes of land cover could be interpreted using digital satellite data. However, seedling stands would be confused with cropland and grassland. Accurate monitoring of regeneration is critical for forecasting future timber supplies. Ownership, size class (poletimber vs. sawtimber), stand origin, old clearcuts, and residential urbanland would be very difficult to interpret with digital satellite data. Small-scale, high-altitude aerial photography could also be used to reliably interpret some categories in Table 1. Seedling stands would be confused with cropland, grassland, and shrubland. Such photography is unsuitable for interpreting ownership and stand origin. These data are available every 5 to 10 years, but would include a wide range of dates for a single Inventory Unit. Alternatively, high resolution, medium- or large-scale aerial photography could be used to interpret all categories in Table 1 except for ownership. It is the only source of new monitoring data which could be acquired directly by FIA, and not subject to priorities and policies of other organizations. Regeneration and type conversions could be detected after 2 years. However, such photography is expensive, and would have to be used for sampling photoplots. Medium-scale aerial photography could be acquired annually, but a 3- to 5-year cycle would be more realistic.

COVER ESTIMATES FROM OTHER AGENCIES

Government agencies routinely gather information about forestlands by mail, telephone canvass, and ground inventories. However, these rarely cover all ownerships, and vary greatly in detail on forest condition, frequency, timeliness, reliability, and definitions. The following lists periodic estimates which might be combined with FIA data to monitor land cover.

The National Resource Inventory (NRI) provides estimates by State of land use/land cover for nonfederal lands every 5 years (USDA Soil Conservation Service 1982). The Census of Agriculture also estimates area of farmland and other land uses by State and county every 5 years (USDC Bureau of the Census 1981). The National Agricultural Statistical Service (NASS) produces annual estimates of area of cropland and total forestland at the State level (USDA Statistical Reporting Service 1983). NASS has produced special estimates of land cover and forest type compatible with FIA definitions (Table 1) for Kansas, Arkansas, and Missouri (May et al. 1986), and a survey that examined harvest and reforestation decisions of NIPF landowners (Fecso et al. 1982). Estimates from these agencies vary from those made by FIA because of differences in definition, timing, sampling, and procedure. However, they might provide a measure of trends in forested area if differences are quantified.

Each year the Forest Service estimates area planted or seeded with trees by State and ownership (USDA Forest Service 1987). Data come from many sources, and vary considerably in quality and accuracy. The area of successful artificial regeneration is overestimated because failures are not considered, and some planted areas were already stocked using FIA definitions. Trends might be monitored with these data if adjusted annually for seedling survival, perhaps using a climatological index.

Information on timber products output (TPO) describes trends and current levels of tree harvest. Most States in the Southeast canvass primary wood-using plants every 1 or 2 years to determine the volume produced and geographic source of all industrial roundwood products (Tansey 1984). Similar information is available for the Midsouth (McWilliams 1986). However, the type of material from which the products are derived is not specified. Some material is not considered growing stock by FIA. TPO does not include logging residue and growing stock removed during conversion in land use.

PREDICTIVE MODELS FOR COVER

Econometric models have been used to predict change in area for land use/forest ownership using economic, social, and policy variables. White and Fleming (1980), Stoll et al. (1984), Brooks (1985), and Alig (1986) all rely on land rent theory. Brooks (1985) also uses models of land allocation to perennial crops as in Houck and Subotnick (1969), French and Matthews (1971), and Minami et al. (1979). Alig (1986) takes advantage of exact prior information to reflect zero sum changes for the total land base. At least three groups of input data are usually required: (1) cross-section and time series data, including FIA data on area by forest ownership (needed to estimate model parameters); (2) current area estimate of the existing forest land base, and; (3) projections or estimates of economic driving variables (necessary to predict changes in land use) such as population estimates and per capita income.

Econometric models have been linked to models of forest succession and cover type dynamics (Alig 1985). These require: (1) current data on the area in each forest type by ownership; (2) probability of a primary disturbance for each type of ownership and forest type; and (3) the conditional probabilities of forest type shifts in response to a primary disturbance (Alig and Wyant 1985). Regional models for the Nation are being developed to predict area changes on a 10-year time increment for long-range planning. Annual projections are possible if an annual time series of estimated economic driving variables is available.

IMPLEMENTING THE KALMAN FILTER

Initial conditions for forestland monitoring using the Kalman filter can be determined from the most current FIA inventory for each Inventory Unit. Areal estimates for all categories of land in Table 1 at time $t=0$ are available for $\hat{\underline{x}}_0$ in equation (4). However, the covariance matrix for estimation error ($\underline{P}_0$ in equation 5) has never been computed because of the complex design used by FIA, which includes systematic sampling, census, and regression data. This problem is being investigated in a related study.

STATE TRANSITION MODEL AND PREDICTION ERROR

Econometric models for an annual time increment, and annual estimates for socioeconomic driving variables, are presently unavailable. Therefore, a more empirical approach is proposed until such are available. Assuming annual transition probabilities among cover types are constant, an estimated state transition matrix ($\hat{\underline{\Phi}}_k$) is readily computed from a previous FIA inventory ($t=-k$) to the most recent FIA inventory ($t=0$) using field classification of permanent plots at both times. For example, 4,878 0.4-ha FIA forested plots were classified in both 1974 ($t=-10$) and 1984 ($t=0$) in NC ($k=10$ years). The ij-th element of $\hat{\underline{\Phi}}_k$ is

$$(\hat{\Phi}_{ij})_k = \frac{N(A_0=i\,|\,A_{-k}=j)}{N(A_{-k}=j)}. \tag{8}$$

where $N(A_0=i\,|\,A_{-k}=j)$ is the number of plots classified as category i at $t=0$ (1984 in NC), given they were classified as category j at $t=-k$ (1974 in NC), and $N(A_{-k}=j)$ is the total number of plots classified as category j at $t=-k$.

Therefore, the columns in $\hat{\underline{\Phi}}_k$ are vectors of independent, estimated, conditional probabilities (see Appendix). Because these probabilities are for k years, they can be converted to a time-invariant transition matrix for one year using

$$\hat{\underline{\Phi}}_1 = (\hat{\underline{\Phi}}_k)^{1/k}, \tag{9}$$

which is derived in the Appendix from equation (1).

If prediction error is caused solely by sampling error in the estimated transition probabilities for k years ($\hat{\underline{\Phi}}_k$), then the covariance matrix for prediction error ($\hat{\underline{Q}}_k$) can be determined using equation (1), the multinominal distribution for each column vector in $\hat{\underline{\Phi}}_k$, and the estimated area variables at time $-k$ and 0 (see Appendix). The covariance matrix for prediction errors in annual estimates ($\hat{\underline{Q}}_1$) is computed from the corresponding matrix for k years using the following (see Appendix)

$$\hat{\underline{Q}}_1 = [\hat{\underline{\Phi}}_1^{k-1} + \hat{\underline{\Phi}}_1^{k-2} + \ldots + \hat{\underline{\Phi}}_1 + \underline{I}]^{-1}\, \hat{\underline{Q}}_k \, [(\hat{\underline{\Phi}}_1^{k-1} + \hat{\underline{\Phi}}_1^{k-2} + \ldots + \hat{\underline{\Phi}}_1 + \underline{I})^{T}]^{-1}. \tag{10}$$

This is an underestimate of prediction error because it ignores change in transition probabilities over time. Realistic estimates of $\underline{Q}_1$ are needed so that proper weight is placed on model predictions relative to measurements. An objective method for scalar inflating $\underline{Q}_1$ to better represent all prediction errors is in the Discussion and Appendix. In the future, this oversimplified model will be replaced with a better econometric model.

COVER MEASUREMENTS USING REMOTE SENSING

Satellite imagery could be periodically classified by FIA for multi-scene areas to map land cover and produce area estimates. In other countries, photointerpreted stand maps might serve the same purpose (e.g., Bonner and Magnussen 1987). Some categories in Table 1 could not be accurately classified (e.g., ownership), and $\underline{H}_t$ would sum these into a less detailed classification system for satellite data (i.e., $m<n$). The measurement relationship matrix ($\underline{H}_t$) could be further determined from an analysis of classification accuracy as commonly done in remote sensing studies (Prisley and Smith 1987). There would

be no sampling error, but error in estimating $\underline{H}_t$ would be included in the measurement error ($\underline{R}_t$) using a multivariate regression estimator or conditional probabilities in a "classification error matrix" (see Appendix).

FIA could obtain aerial photography of photoplots, and photointerpret land cover. Assuming negligible interpretation error, $\underline{H}_t$ would contain ones and zeros, representing the logical association between Table 1 and a less detailed classification system for FIA photointerpretation (e.g., ownership could not be photointerpreted). Sampling error for the photoplots would be used for $\underline{R}_t$. However, classification error can be substantial, and $\underline{H}_t$ would have to be further estimated using ground reference data. The error in estimating $\underline{H}_t$ would be added to the sampling error to compute total measurement error.

COVER MEASUREMENTS FROM OTHER AGENCIES

Extensive estimates of land cover, made annually by NASS and at 5-year intervals by other Federal agencies, have an estimated covariance matrix for sampling errors. This matrix is needed for $\underline{R}_t$ to compute $\underline{G}_t$ in equations (6) and (7). However, these agencies do not produce a detailed classification of forestland. Therefore, the measurement matrix ($\underline{H}_t$) in model (2) must sum many state variables into a few categories. If definitions are compatible, $\underline{H}_t$ will contain zeros or ones, depending upon the logical relationship between land classification systems. However, effects of different definitions and procedures must be quantified; these could be estimated using multivariate regression and corresponding estimates from many geographic areas (e.g., counties or Inventory Units). Alternatively, FIA and another land classification systems might be applied to a randomized set of small plots. The resulting contingency table could be treated as a matrix of conditional probabilities, similar to $\hat{\underline{\Phi}}_k$ and $\hat{\underline{Q}}_k$ (see Appendix). Again, error in estimating $\underline{H}_t$ would have to be added to any sampling error to estimate total measurement error.

VERIFICATION

Many assumptions, approximations, numerical calculations, and estimates are required to apply the Kalman filter. If any are inaccurate, then estimates of land cover or their confidence intervals can be biased, producing serious consequences if undetected. However, the actual distribution of residuals will likely deviate from their expected distribution in presence of significant inaccuracies. The entire time series of multivariate measurement residuals can be standardized and orthogonalized; goodness-of-fit tests could detect significant departures from their expected distribution, and tests of hypotheses used to investigate independence (Appendix). This would identify existence of a problem, but problem isolation and solution could be difficult. Comparison of estimates from the Kalman filter to estimates from a new FIA inventory is the most rigorous test of reliability. This would be possible every 5 to 10 years given present schedules. In a production system, detection of a failure in the filter for one State might suggest potential problems for other States. Serious scrutiny of residuals is necessary for responsible application of the Kalman filter.

DISCUSSION

The Kalman filter has potential for frequent, efficient monitoring of land cover between FIA inventories; however, it also presents formidable challenges. An unexpected distribution of standardized residuals might indicate a poor assumption. The assumption most likely incorrect is time-invariant transition probabilities. This might be remedied using econometric models for cultural changes, and growth and yield models for vegetative succession. Also, the covariance matrix for prediction error, which considers only the sampling error in estimating time-invariant probabilities, could be inflated by a scalar value to represent additional prediction errors caused by changes in transition probabilities. The scalar value might be estimated to maximize the goodness-of-fit of standardized residuals to their expected distribution (Czaplewski 1986). Also, change in transition probabilities over time might be observed directly. Change in cover on permanent photoplots could be efficiently interpreted using a time-series of comparable aerial photography. Future NASS or Bureau of Census surveys could include estimates of timber harvest, forest regeneration, conversion of land use, and change in type of ownership, especially for NIPF lands. Annual estimates of seeding and planting rates, supplemented by survival estimates, might improve predictions of regeneration rates for planted stands. Annual estimates of TPO might improve predicted area of forest converted to other cover types because of harvest. These would require the Kalman filter to simultaneously estimate state variables and rate parameters.

Some existing sources of monitoring data might not be useful because they do not use FIA definitions (e.g., SCS, NASS, Bureau of Census, TPO, and Planting Reports). Definitions and criteria for minimum stand size vary. Measurements of aggregations of many variables might poorly represent changes which vary considerably among components (e.g., clearcut rate on industrial lands might be much different than on non-industrial lands, but this difference would be ignored if direct observation of clearcut area was not identified by ownership). The expense in quantifying these differences might not justify a marginal increase in efficiency. Rather, new sources of frequent monitoring data, such as remote sensing or surveys of forest landowners might be more cost effective.

The land classification system in Table 1 contains 418 categories. Each requires a separate state variable. More variables in the state vector would be required for simultaneous estimation of rate parameters. The Kalman filter is rarely successful for systems with more than 60 such variables, and the classification system must be simplified. This could be reduced to 48 classes if non-forested cover types are not differentiated by ownership, nor planted and nonstocked stands by forest type; and land ownership classes condensed into 3 categories: public, forest industry, other private.

This proposal is speculative, and there are major questions regarding implementation. Will insurmountable problems be encountered using remote sensing and ancillary data of varying quality as monitoring data, and FIA inventories as initial conditions and the basis for an empirical model of change in cover? Will monitoring data for land/forest cover and rates of change and inflation of prediction error compensate for a predictive model that assumes constant transition probabilities among cover types. Can econometric models be formulated to better predict annual changes in cover. These questions are being addressed in an ongoing study for the State of North Carolina.

LITERATURE CITED

APPENDIX

Available from authors upon request.

STUDY DESIGN FOR GROWTH RESPONSE OF LOBLOLLY PINE TO VARYING DEGREES OF HARDWOOD AND HERBACEOUS VEGETATION CONTROL

Glenn R. Glover, Bruce R. Zutter and Jerre L. Creighton

ABSTRACT. Pine growth response studies installed by members of the Auburn University Silvicultural Herbicide Cooperative and others have demonstrated increased pine survival and growth through vegetation control. Most of these studies were one-point-in-time installations over a fairly narrow range of vegetation conditions. In order to justify operational vegetation control treatments and continued screening of new forestry chemicals, quantification of the effects of degree and timing of herbaceous and woody vegetation control and resultant level of competing vegetation on short- and long-term growth of loblolly pine is needed.

An experiment is being installed over a four-year period across the southern United States which will consist of 88 locations of five plots each (440 plots total). Treatments will be applied to 0.13-ha plots, with an interior measurement plot of 0.06 ha. Study locations will be established in newly planted to five-year-old plantations. Varying levels of initial arborescent hardwood density (ranging from <1200 to >7400 rootstocks per ha) and loblolly pine site index (from <17 m to >20 m, base age 25 years) will be included. Pine and hardwoods will be presampled to ensure uniformity in density and size within a location. Herbicide treatment of individual hardwood stems will be used to create varying levels of residual hardwood vegetation, given an initial level at each location. Herbaceous vegetation control will be complete for one year following hardwood treatment, or not at all. Pine, hardwood and herbaceous vegetation will be quantified at specified times during the life of the stand. The study will be followed through rotation.

The study is designed as a response surface approach. Due to manpower restrictions and the unlikely occurrence of some factor combinations, not all cells of the full data matrix will be filled. Data cells were selected to provide sufficient information to define pine response as a function of vegetation and site factors, with particular strength in areas of practical significance. Specifics of the data matrix definition, plot design, presampling scheme, treatments and treatment procedures, measurement variables and procedures, measurement schedule and expected analysis of the data are presented.

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INTRODUCTION

The objective of the described study is to quantify the effects of degree and timing of herbaceous and hardwood vegetation control and resultant level of competing vegetation on short- and long-term growth of loblolly pine. The study will consist of approximately 88 locations of five plots each, or 440 plots total, located across the 13 southeastern United States. The study is being installed by members of the Auburn University Silvicultural Herbicide Cooperative, a forest industry, state, U.S. Forest Service and university research cooperative whose goals are to develop and enhance the use of herbicides in forest management in the southern United States. Actual field installation and measurement will be accomplished by people with diverse training, from technicians to foresters with advanced degrees. Therefore, the study had to be designed in a manner that could be understood and implemented by individuals with diverse educational backgrounds.

DEFINITION OF DATA MATRIX

Locations are to be established in newly planted (pine age 0) to five-year-old loblolly pine plantations on mesic sites where the primary competing hardwood species are oaks (Quercus spp.), sweetgum (Liquidambar styraciflua), hickories (Carya spp.) and/or maples (Acer spp.). Wetlands or flatwoods areas are to be avoided. Locations should not have been fertilized. Plots will be installed in areas of low (<17 m), medium (17-20 m) and high (>20 m) loblolly pine site index (base age 25 years). There are no restrictions on site preparation methods, except that chemically site prepared areas should be at least two years old.

Sites planted with genetically improved trees are preferred, with a surviving density of planted pines of at least 1235 trees/ha (pine age 0), 1112 trees/ha (pine age 1), 988 trees/ha (pine age 2 or 3) or 864 trees/ha (pine age 4 or 5). There will be no more than 2223 surviving pines/ha and no more than 123 natural pines/ha. Varying levels of initial (pre-treatment) arborescent hardwoods (trees capable of claiming a place in the canopy) will be included, as defined in Table 1.

Table 1. Hardwood density classes by pine age at treatment.

Hardwood density class	Pine age at treatment (years from planting) 0	1	2-3	4-5
	(number of arborescent hardwood rootstocks/ha)			
A	<1237	<1237	<1237	<1237
B	1237-2470	1237-2470	1237-3705	1237-4940
C	2471-3705	2471-4940	3706-6175	4941-7410
D	>3705	>4940	>6175	>7410

The combinations of pine age at treatment, site index and initial hardwood level yield a total of 72 initial condition data cells. The inclusion of control versus no control of the herbaceous vegetation doubles this to 144 data cells. Given the constraints of manpower and the fact that some combinations of factors would be uncommon, thus of little interest, the actual allocation of plots to data cells was made based on combinations of factors that relate to plausible management schemes. The number of plots assigned to each data cell is shown in Table 2. Although the distribution of plots covers the entire data matrix, more emphasis was given to the medium site index level, ages 1-4, initial hardwood levels B-D and to no herbaceous control. Herbaceous control plots were further concentrated at pine ages 0-2. These emphases were based on information from existing hardwood and herbaceous control studies, acreage distribution by vegetation and site index classes, distribution of vegetation problems and on perceived management trends. That is, more plots were allocated to the more important problem areas in the data matrix.

Table 2. Distribution of plots by pine age at treatment, site index class, initial hardwood level and herbaceous vegetation control.

	SITE INDEX LEVEL																							
	Low								Medium								High							
	INITIAL HARDWOOD LEVEL																							
	A		B		C		D		A		B		C		D		A		B		C		D	
	HERBACEOUS CONTROL																							
Pine age (yr)	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
									(number of plots)															
0	-	-	2	3	-	-	2	3	2	3	-	-	3	7	2	3	-	-	2	3	3	7	2	5
1	2	3	-	-	2	3	-	-	2	3	6	9	5	10	3	7	2	3	4	6	2	3	3	7
2	-	-	2	3	-	-	1	4	5	5	3	7	3	12	2	8	2	3	4	6	2	8	1	4
3	2	3	-	-	1	4	-	-	2	3	2	13	1	14	1	9	1	4	2	8	-	5	1	9
4	-	-	1	4	-	-	-	5	2	8	-	10	2	13	1	9	1	4	2	8	1	9	-	5
5	-	-	-	5	-	-	1	4	1	4	-	-	1	9	-	5	-	-	1	4	-	10	-	5
TOTALS[1]																								
HERB. CONT.	4	6	5	15	3	7	4	16	14	26	11	39	15	65	9	41	6	14	15	35	8	42	7	33
HARD. LEVEL	--10--		--20--		--10--		--20--		--40--		--50--		--80--		--50--		--20--		--50--		--50--		--40--	
SITE INDEX	--------------60--------------								--------------220--------------								--------------160--------------							

[1] Total number of plots by pine age: 0--50, 1--85, 2--85, 3--85, 4--85, 5--50
Total number of plots by initial hardwood level: A--70, B--120, C--140, D--110
Total number of plots by herbaceous control: Yes--101, No--339

PLOT DESIGN AND PRESAMPLING

The study is designed for response surface analysis and sets of plots are not replicated at a location. Five 0.13-ha square treatment plots (TP) are established at each location. A 0.06-ha square pine measurement plot (PMP) is established inside each TP. In each quadrant of the PMP, two 14.38-m^2 (2.14 m radius) competition measurement plots (CMP) are randomly established (eight total per PMP) for evaluation of arborescent hardwoods (through pine age 8), and non-arborescent hardwoods and herbaceous cover estimates. Five 1.0-m^2 herbaceous clip plots are also randomly located in each PMP (first year only). Plot layout is shown in Figure 1.

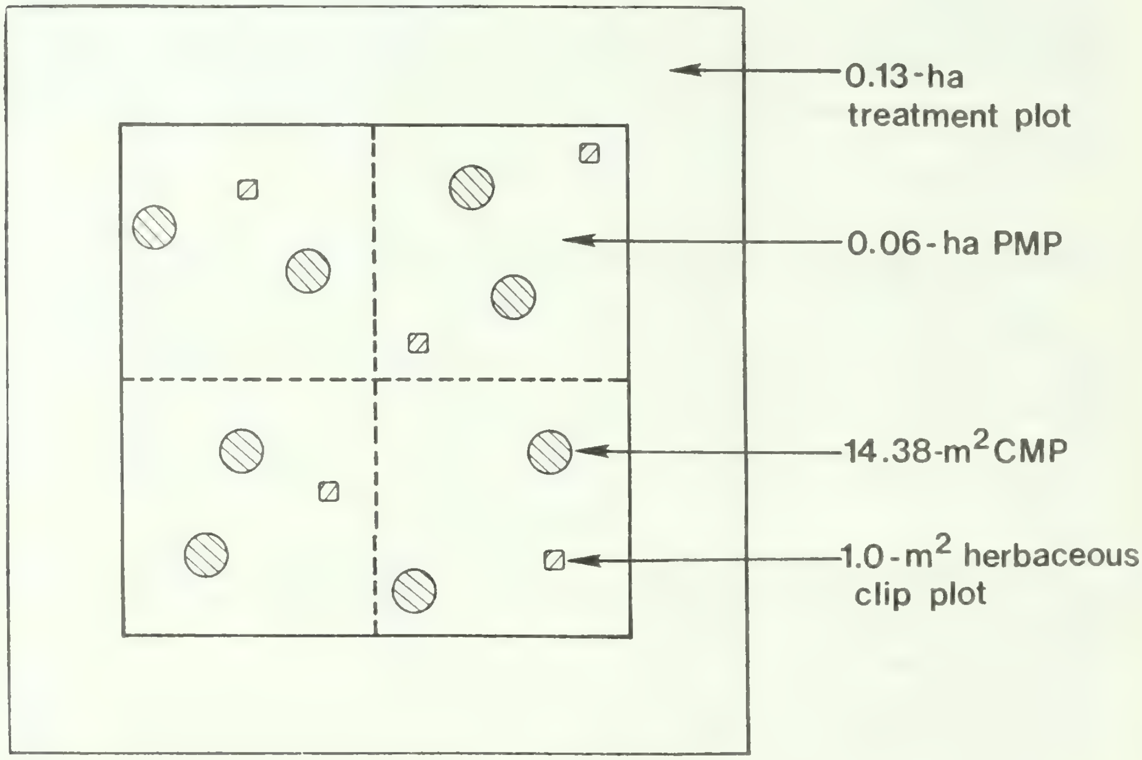

Figure 1. Treatment, pine measurement (PMP), competition measurement (CMP) and herbaceous clip plot layout.

In establishing a location of five plots, more than five plots are initially pinned. Each temporary plot is presampled to assure uniformity in pine density, pine height and hardwood rootstock density. All pines on the PMP are counted and measured for total height. Five 1.83-m-wide strips are run across each PMP for estimation of hardwood rootstock density. The five plots which are most uniform in terms of pine density and mean total height and hardwood rootstock density are utilized (the location is rejected if one of the five PMP's fails to meet any of the following criteria: pine density within ±10% of mean density, mean pine total height within ±10% of overall mean total height or hardwood rootstock density within ±20% of mean hardwood rootstock density). After presampling, a staff member from Auburn visits and approves each location before further measurement and treatment. Following approval, but before treatment, the pines are permanently marked and PMP's and CMP's are permanently monumented and measured (measurements are detailed later).

TREATMENTS

Once plots at a location have met specifications, treatments are assigned by the Auburn staff in order to ensure completion of the data matrix and geographical representation of treatments. Hardwood treatments are designed to reduce a particular level of rootstocks to a specified lower level or to zero. For example, if a location at age 4 had an average of 5849 rootstocks per acre, it would be in hardwood class "C". Possible treatments could leave a plot at level "C", or reduce it to a levels "B", "A" or to zero (complete hardwood control). A list of possible hardwood treatments is given in Table 3. Hardwood control is accomplished by a dormant season basal bark application of triclopyr ester in diesel fuel. One or more of the plots could also include complete herbaceous control for one year (the first year following hardwood control). Herbaceous control is included to simulate the control of herbaceous vegetation that is obtained with some pine release herbicides and to aid in evaluation of the relative impacts of hardwood versus herbaceous vegetation on pine growth. Herbaceous control is accomplished by an early-season broadcast application of sulfometuron, with followup directed applications of glyphosate. At each location, one plot is always left as an untreated check and one plot receives complete hardwood control. All hardwood and herbaceous treatments are made during the first year of establishment only.

To obtain the desired level of hardwood reduction and prevent biased selection of individual hardwoods for treatment, the following plan was devised. Twenty objects of two different colors (e.g. red and white marbles) are allocated in the proportion necessary to accomplish the desired hardwood reduction level. For example, if 65% hardwood reduction is desired, then 13 red and 7 white marbles are placed in one pocket of a nail apron. The 0.13-ha treatment plot is divided into relatively narrow strips (e.g. 2 m) by stretching strings through the plot. As each individual hardwood rootstock is approached, a marble is drawn. If the marble is red, the rootstock is treated; if the marble is white, the rootstock is left untreated. The drawn marble is placed into a second pocket of the nail apron (random sampling, without replacement). Therefore, the decision whether to treat a rootstock is random and the desired proportion of treated rootstocks is accomplished every 20 hardwoods, ensuring a distribution of treated rootstocks across the entire plot.

Table 3. Hardwood reduction treatments by initial and residual hardwood levels and by pine age at treatment.

	Pine age (years from planting)			
	0	1	2-3	4-5
Initial, residual hardwood level[a]	(approximate percent reduction in arborescent species rootstocks)			
A,A	0	0	0	0
A,O	100	100	100	100
B,B	0	0	0	0
B,A	65	65	75	70
B,O	100	100	100	100
C,C	0	0	0	0
C,B	40	50	50	50
C,A	80	85	90	90
C,O	100	100	100	100
D,D	0	0	0	0
D,C	30	40	35	30
D,B	55	70	60	65
D,A	85	90	90	90
D,O	100	100	100	100

[a] "O" residual level implies complete control of hardwoods.

MEASUREMENT PROCEDURE AND SCHEDULE

Prior to treatment and at specified ages after treatment, the pines, hardwoods and herbaceous vegetation will be measured on appropriate measurement subplots according to the schedule outlined in Table 4. Measurements for each of the components include:

PINES: All pines
- -- stem count, total height, condition code--all evaluations,
- -- VDF Free-To-Grow classification--to age 8,
- -- crown class--starting at age 8 and thereafter,
- -- dbh--starting at age 5 and thereafter.

Subsample of 20 pines per PMP
- -- height to crown base--all evaluations,
- -- diameter at 15 cm above groundline--to age 5
- -- crown width--to age 8.

HARDWOODS:
- -- species and height class--all evaluations,
- -- crown width (bud to bud)--to age 8,
- -- dbh--starting at pine age 8 and thereafter. (hardwoods will be measured only on CMP's to age 8, on the entire PMP thereafter.)

HERBACEOUS:
- -- percent ground cover of all herbaceous vegetation on each CMP--all evaluations,
- -- percent ground cover and species of each of the five species with the greatest cover--all evaluations,
- -- dry weight of herbaceous vegetation clipped from five randomly located 1.0-m^2 subplots in each PMP--end of the first year after treatment only.

NON-ARBORESCENT HARDWOODS:
- -- species, percent cover and mean height on each CMP--all evaluations.

Table 4. Measurement schedule for all vegetation components by treatment and measurement age of pine.

	Measurement age of pine (years)													
Treatment age (yrs)	0	1	2	3	4	5	6	7	8	9	10	11	15	5-year intervals to rotation
0	X	X		X		X			X			X	X	X
1		X		X		X			X			X	X	X
2			X		X	X			X			X	X	X
3				X		X			X			X	X	X
4					X	X	X		X			X	X	X
5						X		X	X			X	X	X

ANALYSIS

The purpose of this study is to describe the effects of competing hardwood and herbaceous vegetation on pine survival, growth and yield, not to develop a comprehensive growth projection system. Relationships and models derived from this study should be suitable to modify, adjust or include in existing and developed yield models. The primary analysis will be investigation of pine-competing vegetation growth relationships, and development of models of these relationships using regression techniques. Single and multi-dimensional response surface models of desired pine response variables as a function of hardwood and/or herbaceous variables will be developed using appropriate mathematical models. It should be noted that actual measured values will be used in the analysis. Classifications used in defining the data matrix were used only to assure a suitable range of data.

Figure 2 shows a hypothetical response surface of pine yield (in any units) as a function of initial and residual hardwood level. The upper surface might represent the relationship in the presence of herbaceous vegetation control, where the lower surface would be without herbaceous control. The relationships could also portray age at treatment, where the upper surface would represent a younger age at treatment, resulting in increased pine yield.

This paper briefly summarizes the major points of the study. A full work plan is available from the authors.

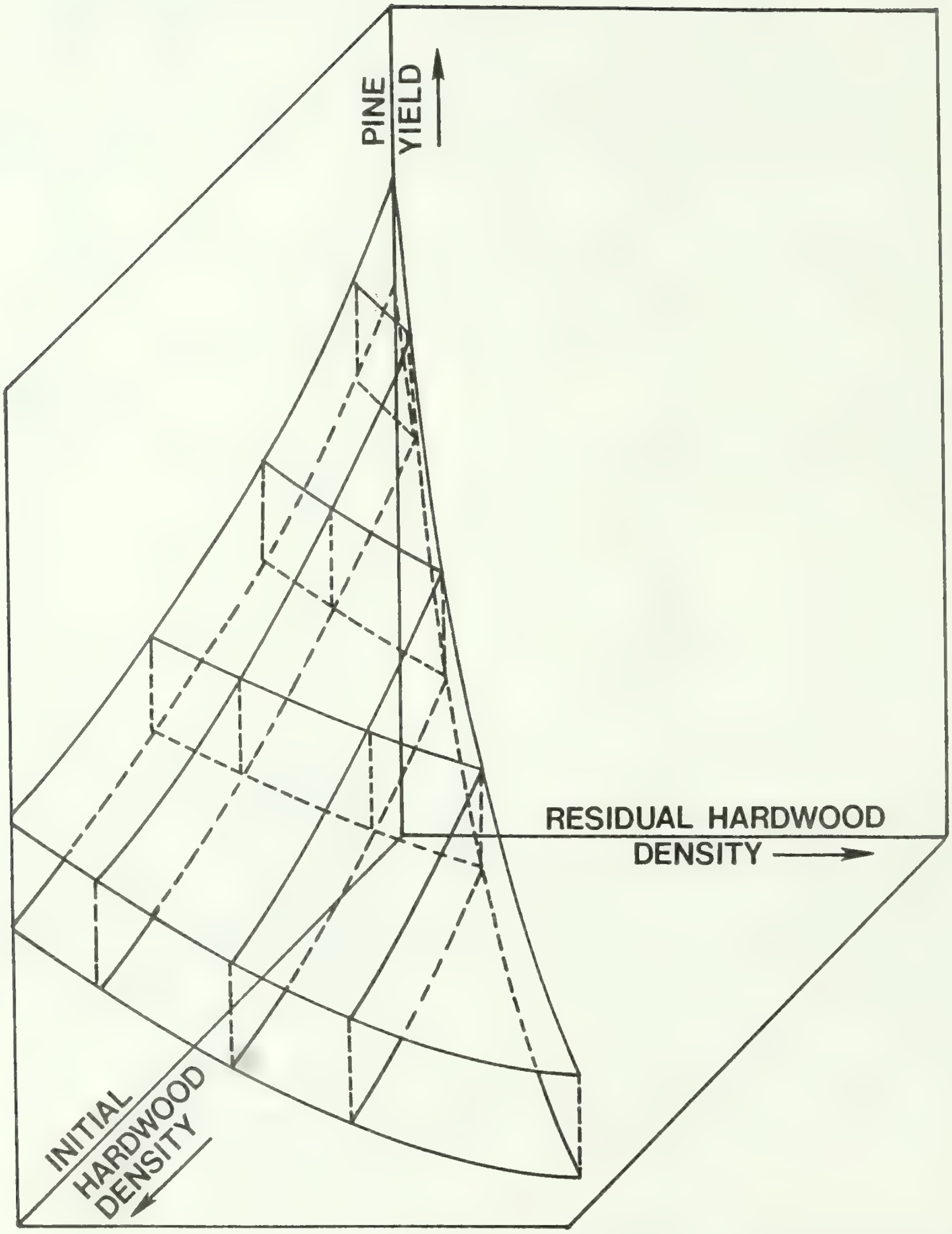

Figure 2. Hypothesized response surfaces for pine yield as a function of initial and residual hardwood density.

GROWTH ON PERMANENT ANGLE-COUNT PLOTS, HISTORICAL ESTIMATION PROCEDURES THROUGH CRITICAL HEIGHT SAMPLING

Kim Iles[1]

ABSTRACT. Measuring stand growth on "Angle-count" or Variable Plot permanent plots should present few serious problems. The logic of all these estimation schemes is best demonstrated by solid geometry and the idea of sampling the "depth of wood" above a sample point. Critical Height Sampling, or varieties of it, can be used to give a compatible estimator of low variance.

INTRODUCTION

Perhaps it is because I specialize in Variable Plot Sampling that I hear these complaints more often than other people. When the topic of remeasured plots is at hand and variable plots are mentioned, you get a predictable reaction among inventory foresters and managers. "Oh, you can't use them for remeasured plots, they just don't work out". "There's some problem with 'ongrowth trees' so that the results are not 'compatible' with each other". The problem is usually unstated, but presumed to be lurking close by. "There are some new systems to analyze them, but the geniuses who think them up (sneer, sneer) are the only ones who know how they work, and I doubt if they are sensible". There are, of course, more subtle quotes, but they all get the point across. "It is perhaps impossible, certainly hard, and very possibly foolish".

Now most of this attitude is wrong, but why does it happen? These are smart people. Why should they be confused? To me there is little doubt why this takes place. The literature which discusses these problems frequently has lots of algebra and little logic. The discussions have much probability and little solid geometry. In my opinion, the fault lies most often with the biometricians and editors, who are satisfied with unassailable mathematics rather than clarity of ideas. No small thanks to universities here, who do not much care if an article is readable or usable, as long as it is publishable. The goal of a greater number of publications should be to convince readers of the soundness of basic ideas. There is a need for a way of thinking about these concepts that allows people to see how modifications can be made, and what the essential ideas are. This seldom requires math, but a believable logical structure makes the math easier to struggle through.

There are reasons for the difficulty in understanding this sampling system. One is the tendency to read only the most recent literature. Researchers are often distracted by every rabbit that crosses their path, and it is hard for a casual reader to see, in the short run (5 to 10 years), where these discussions may be leading or where they originated. In fact, the leaders in this field — Grosenbaugh, Furnival, Bitterlich, and Beers to name a few — had the basic answers in a workable form very early in the game. Most of their logic has not been improved upon.

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And why, by contrast, have fixed plots been so popular and well accepted? Is it their proven record of success? Are there underlying mathematical strengths? Probably not. The fact is that any bozo off the street can quickly understand how fixed plots work, and can believe that the logic for fancier applications could be worked out from this basically sound principle. Compare this to some of the variable plot literature on permanent variable plots. No contest.

Yet these two methods have a great deal in common, and only a few differences. The ideas can be explained with little math, and in terms of sold geometry. This is true for the techniques for variable permanent plots from Grosenbaugh's (1958) first discussions on the topic up through the more recent applications of Critical Height Sampling.

I believe that the most general way to view the sampling method, and the most likely to be understood and applied by most people, is to view it as measuring the vertical "depth of wood" on the forest floor. For a fixed plot scheme, imagine a 1/10 acre circular plot around each tree (I am also convinced that this "tree centered" view is the most productive). We now squash each tree volume down onto this circle forming a solid disc. The sample scheme then consists of sampling the "depth" of wood which lies over a random sample point. The several overlapping discs at a particular sample point identify the trees which are associated with that sample point. It is easy to see that such a system would be unbiased, and to visualize the variance of the sampling system as the undulation of these depths across the forest surface. There is little problem in generalizing this system to a circle surrounding the tree which is not a constant size, but varies for any reason, one of which may be tree diameter such as in Variable Plot Sampling. This is a simple and tractable way of thinking about fixed or variable plots, both temporary and permanent in nature.

These discs are proportional to the usual term "VBAR" (Volume to Basal Area Ratio) and can be thought of in those terms. What would happen if we measured at the same point over a span of time? We would have the situation shown in Figure 1.

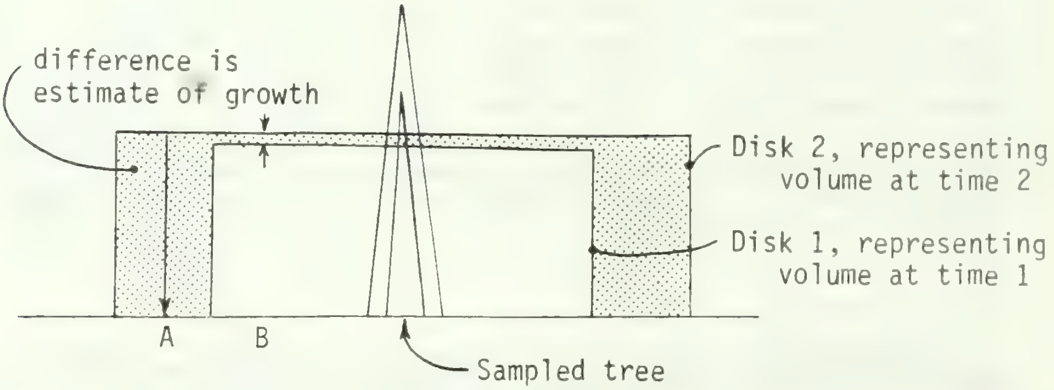
difference is estimate of growth
Disk 2, representing volume at time 2
Disk 1, representing volume at time 1
A
B
Sampled tree

Figure 1. Simple Remeasurement Method

SIMPLE REMEASUREMENT METHOD

This is the classic remeasurement situation, and while a number of trees would be involved, only one is illustrated here to minimize graphic clutter. The shaded area (a cross-section of the discs at time 1 and time 2) shows the volume growth during the time interval. It is exaggerated for clarity. The disc size is different at time 2, so the "depth" of volume difference during the interval is not constant everywhere. If the sample point happens to be at point A, the estimated growth at that point is large, but at point B it would be small. It is obvious, however, that the growth estimate does in the long run equal the difference in the disc (tree) volumes at each time. It is also obvious that the growth estimate is quite variable. The growth estimate, which is quite simply the difference in "wood depth" at the two measurements is the oldest and simplest of growth measurements. It was most recently restated by Van Deusen et al. (1986a).

FIXING PLOT SIZE

Grosenbaugh (1958) realized that the easiest way to stabilize the growth estimate was not to change the plot size at time 2. After all, there is no need to change the size of any plot over time, whether it is an equal size for each tree (as in most fixed plot samples) or whether they were originally of different sizes. We don't change the 1/10 acre plots over time just because trees grow — why should we change the variable plots' original size just because the trees grew in diameter? The method can be easily illustrated by Figure 2.

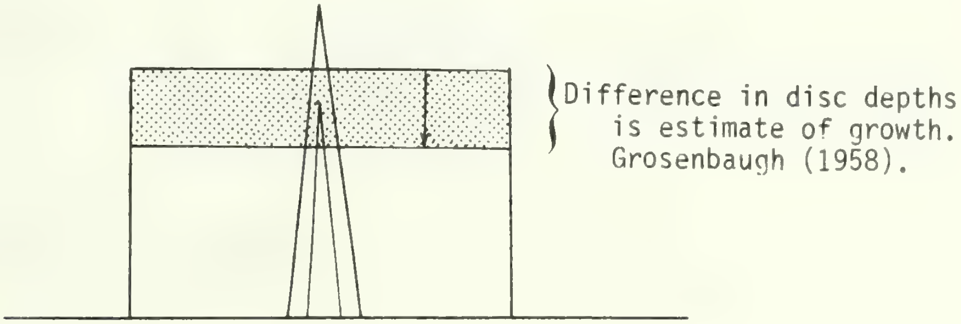
Difference in disc depths is estimate of growth. Grosenbaugh (1958).

Figure 2. Plot Size Stabilized

This was a sensible and adequate solution. There was no need to take an angle gauge along at the remeasurement time. Change in volume was simply computed and fairly consistent as you can see in the diagram. The large changes only occurred with mortality.

"COMPATIBILITY" OF THE VOLUME ESTIMATE

But the temptation was too strong. People insisted upon taking along their angle gauges at time 2, and found that there were "new trees" leaping upon their sample plots. (They were at point A in Figure 1 and were disturbed about it). There were several early articles like Beers and Miller (1964) and

Grosenbaugh (1958) that told them the answer — "don't worry about it, just don't change the plot size, and you will get better answers. You could use them, but you are better off ignoring them," or words to that effect. Still, there was a lot of teeth grinding about these "new trees." Grosenbaugh even suggested that these new trees could be included during the next growing cycle, but that didn't catch on well.

There was great concern over the fact that the "initial volume" added to the (best) estimate of growth did not give the "final volume" with these new trees included. These 3 numbers weren't "compatible." Of course they weren't, they had changed the plot size. The same thing would have happened if they had changed from a 1/10 acre plot to a 1/7 acre plot. The original volume estimate plus growth (based on the 1/10 acre plots) would not match the final estimate (based on the 1/7 acre plots). But people felt compelled to change plot sizes with unequal area plots, while it was equally obvious to maintain the size of equal area plots. The "problem of incompatibility" is solved the same way in either system. (1) Don't change the plot size (for most consistent growth estimates), or (2) Do a simple subtraction to get a compatible answer. There are at least two other solutions. First, you could change the estimate of both the original and final inventory based on the new information and do it in such a way that the difference equals the estimated growth. I do not know of a good reference on this, but I am sure it has been suggested, and perhaps adopted by some organizations. Second, you could look for a "compatible estimator" that was nearly as constant as Grosenbaugh's suggestion.

CRITICAL HEIGHT SAMPLING

In 1974, I developed a sampling scheme which measured the penetration of vertical rays through tree stems, essentially measuring the "depth of wood" through the tree shape, rather than a flattened tree disc (Iles, 1974). Figure 3 shows the basic idea.

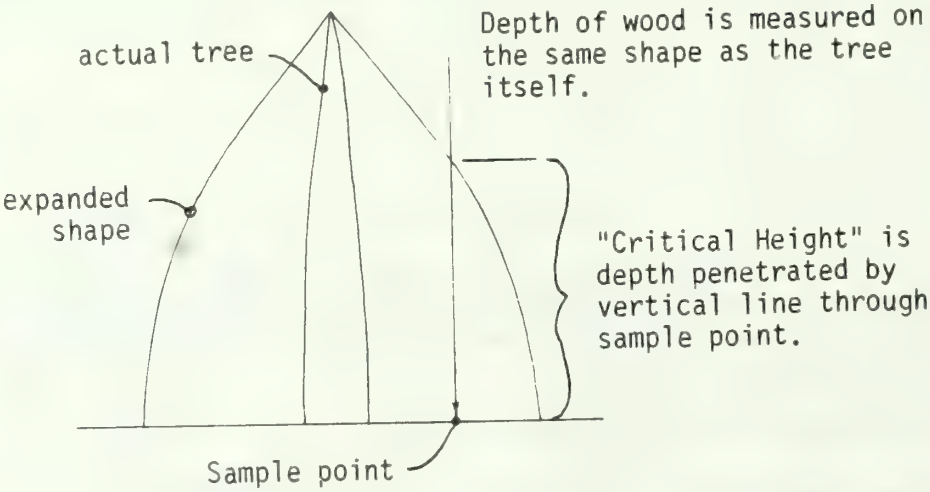
actual tree
Depth of wood is measured on the same shape as the tree itself.
expanded shape
"Critical Height" is depth penetrated by vertical line through sample point.
Sample point

Figure 3. Critical Height Estimator

Since a sample scheme measures the same mass (whatever the shape), it was clearly unbiased and would have a variance based on the stem shape and how these shapes would overlap due to tree size and spacing (just as discs would overlap in a standard scheme). It required no volume tables and very simple measurements. Assuming that such a simple system must have been derived before, I made a search of the literature and eventually found a translated Japanese article by Kitamura (1968), leading to an earlier work (1964). It was clear that there were no essential differences in the methods, and that Kitamura had clear priority, so I have adopted his term "Critical Height Sampling" in subsequent articles. The essential change is that we no longer need to sample a disc shape, but can sample the actual tree shape, or a "pseudo-tree" with the same volume but more convenient shape.

Initial trials of Critical Height as a sampling scheme (Iles, 1979b) were not impressive. It seemed to have the same variability as a standard variable plot scheme. In addition, the field measurements were awkward and while it eliminated volume tables, it did not eliminate the estimation of bark thickness.

C.H. IN GROWTH ESTIMATION

It did seem to offer possibilities in the growth of plots. As the tree adds a "shell of growth" over time, the critical height of the tree changes in exactly the same way, as illustrated in Figure 4.

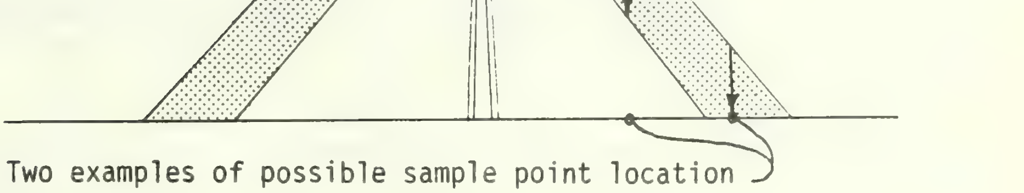
"depth" of shell gives growth estimate
Two examples of possible sample point location

Figure 4. Volume Change with Critical Height Sampling

This offered a compatible estimator, but with a much reduced variability over Figure 1, and possibly (due to tree spacing) a slight improvement over Figure 2. Although Bitterlich (1978, 1983) has kindly labeled the system "Iles's method," there is always the possibility that it was suggested earlier by Kitamura. Since most of his work is only available in Japanese or German, I am sure that a number of such ideas have been addressed in parallel. Since it is so difficult to find the literature on critical height sampling for temporary and permanent plots, I have tried to give a reasonably complete list in the literature citations. I would be glad to help readers obtain copies if they have difficulty in finding them.

A short time later Flewelling (1981) proposed a similar estimator, illustrated by Figure 5, and I believe that this paper was the origin of the term "compatible estimator" in reference to permanent variable plots, although the problem had been recognized much earlier.

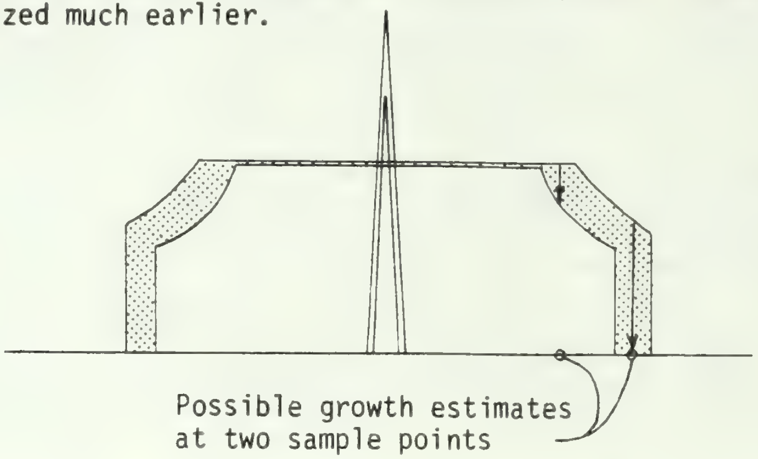

Figure 5. Flewelling's Growth Estimator

There have been several articles on Critical Height Sampling in the past few years, but they have suggested no real improvement to CH sampling as it was originally proposed. They have nicely illustrated the mathematics from several different perspectives, and that has been most useful. What is badly needed are some actual field trials, and some examples of remeasuring point samples. These require the distances from sample point to measured tree. Thus far I have been unable to find such a data set, and would be grateful if readers could assist me in obtaining one.

MODIFYING THE C.H. ESTIMATE

The only really new idea I have seen in a long time is by Van Deusen and Lynch (1987). He has suggested adding what might be called a "modifier shape" to the usual critical height shape. The combination has the same average value as the original critical height, but produces a "pseudo-tree" or "composite estimate" of a different shape. This is illustrated in Figure 6.

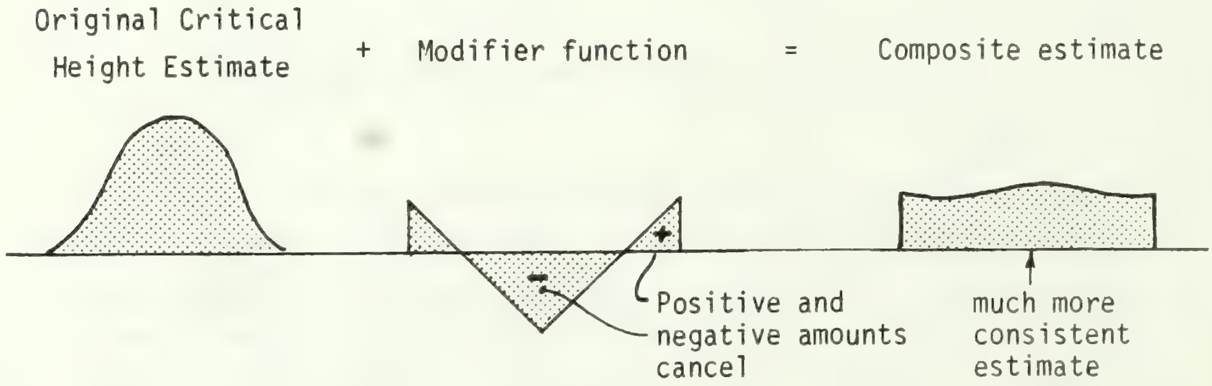

Figure 6. Van Deusen's Modification Procedure

Since it has a shape which includes positive and negative values, the modifier has an expected value of zero. Since the expection is zero for the modifier function the final average estimated volume will not change, but will have a different variance. His paper suggested producing a disc shape, which might not be desirable from a sampling viewpoint or for remeasurement of sample plots, but that is not really the point. The zero expectation modifier controls the shape of the pseudo-tree, and that is a very clever adaptation of the general method known as "antithetic variables" (Rubinstein, 1985). While such general methods are readily available in the statistical literature, they are not often adapted so cleverly to real uses. In this case, the product is very close to the classic variable plot sampling method, but eliminates the need for volume tables to calculate VBAR. When the modifying function doesn't exactly compensate for the tree taper, the composite estimate is not exactly "flat," but can be assumed to have virtually the same characteristics for sampling as ordinary variable plot sampling, about which we have a good deal of practical knowledge.

SUMMARY

My purpose here has been to emphasize that all these approaches can be illustrated and understood by simple geometry. I would contend that is easier to understand, relate and modify these systems by thinking about them in this way, and that their variance is more obviously seen using this approach. This is particularly true for students, forest managers, and administrators. It is not so important to provide these people with statistical proofs as to give them a mental model which they can appreciate and to which they can relate new ideas. Until this is done almost as clearly as fixed plot sampling, there is little chance of these techniques being given the credit they deserve.

While my own preference for growth measurement is toward installing standard fixed plots, it is because I anticipate that it will be easier to overlay new detailed studies (of as yet unspecified nature). For volume growth studies, however, I think that variable plots can be just as valuable and perhaps more efficient than standard fixed plots. This makes them just as useful as other forms of data for validating and building models. Past information in this form should therefore not be ignored or undervalued.

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MEASUREMENT OF DATA FOR TREE MODELS

Pekka Kilkki[1]

ABSTRACT: To solve the problems of inadequate data for modelling and optimal combination of tree models and sample tree measurements in forest inventories, a tree study within the framework of the Finnish National Forest Inventory (NFI) will begin in 1988. The data collection lasts for two years and altogether 6000 felled sample trees, 2000 Scots pines, 2000 Norway spruces, and 2000 birches will be measured, i.e. the data will represent over 95 percent of the country's trees. Each tree is cut into sections and detailed stem and crown analyses are carried out. The data will be used to study the following topics: (1) taper curve, (2) taper curve change, (3) increment variation, (4) height-age site indices, (5) tree biomass, (6) quality of the stem, (7) health of trees, (8) nutrient condition of the tree and its environment.

INTRODUCTION

Finnish National Forest Inventory (NFI) is carried out on a continuous basis and it covers the whole country once in less than ten years. The sampling unit is a relascope point cluster. Altogether 75000 relascope points, over 500000 tallied trees and around 100000 sample trees are measured during each round of inventory.

Tree species, dbh, and quality of the tree (saw timber - pulpwood) are recorded from the tallied trees. The additional variables for the sample trees consist of height, the height of the dead and live crown limit, upper diameter at the height of 6 meters, age, thickness of the bark at the breast height, diameter increment of the last 5 years at the breast height, and height increment of the last 5 years for the conifers. Models based on sample tree measurements are used to derive the sample tree variables for the tallied trees. The estimates for stem volume, volumes of the timber assortments, and the volume increment based on sample tree variables are calculated from the general taper curve models (Laasasenaho 1983).

The number of the sample trees in the current inventory most probably exceeds their need. With a more efficient use of the data, the number of field measurements might be reduced. On the other hand, there are still problems which can be solved neither by the NFI sample tree measurements nor by

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the existing data of the trees measured by sections. The usefulness of the existing data is limited because they represent ill-definend populations, information is mainly about the tree individuals, and only part of the interesting variables are available in each set of data. Among the most urgent problems not satisfactorily solved with the present data sets are:

1. Individual tree growth models have replaced stand models in growth simulation. Yet, our knowledge of the individual tree growth is inadequate. Models for taper curve changes are unsatisfactory or nonexisting.
2. Site classification based on height suffers from inaccurate height development models.
3. The models for the above-ground tree biomass of the tree are unsatisfactory.
4. Measurements, not ocular estimates are needed to study the damages caused by air pollution.
5. Recent development in taper curve modelling (Lappi 1986) suggests that less measurements may be needed for a given accuracy if the prior information of the tree models is used efficiently. Lappi decomposes the total variation in stem dimensions into two components: within-stand variation and between-stand variation. Consequently, the data must provide information for these variance components.

To solve these problems felled sample tree data will be measured in connection with the Finnish NFI in years 1988 and 1989. Altogether 6000 trees, 2000 Scots pines, 2000 Norway spruces, and 2000 birches will be felled and measured in detail both in field and laboratory. The trees will be chosen as to represent the whole tree population of Finland. A pilot study for the development of the measurement techniques was carried out in summer 1987.

MEASUREMENT OF DATA

The country is divided into approximately 2000 squares and from each square a sample point is chosen randomly. Its site and and growing stock are decribed using the standard NFI variables. Soil samples are taken to measure the nutrients.

Trees with dbh under 4.5 cm are tallied on a circle with radius 2.5 m, trees with dbh between 4.5 and 10.5 cm on a circle with radius 5.64 m, and trees with dbh over 10.5 cm on a circle with radius 9.77 m or on the area of 300 sq.m. The trees are mapped in the polar coordinate system. In addition to the tree species, quality of the tree (saw log - pulp wood) and dbh, the height is measured for every tree. On circles with radiuses half of the above radiuses the age is measured and increment cores at the breast height are taken from all trees.

At most five sample trees are felled. They are chosen using the basal area factor 1. Furthermore, it is required that the felled sample trees must be closer than 7.77 meters from the center of the plot.

Sixteen sections at relative heights are cut from each felled tree. The quality of the stem is recorded and four wood samples are analyzed in laboratory to determine the density of the wood in different parts of the stem. The biomass of the crown - divided into branch wood over bark and needles or leaves - is estimated by tallying all branches and by taking a number of sample branches whose wet and dry masses are measured. Nutrients are analyzed from the needles. The age of the oldest needles is determined and the condition of the needles is analyzed from sample branches.

In addition to the measured variables, a large number of variables describing the tree and its neighborhood can be calculated.

The total measurement costs of the data will exceed $ 1 mill.

ANALYSIS OF DATA

The modelling will be aimed at such models which can be efficiently integrated with the inventory and management planning systems. Usually the tree models are not used to provide estimates for an individual tree but for a larger set of trees, e.g., for a forest stand. Consequently, the total variation of the tree variables will be divided into the between-stand variation and within-stand variation (see Kilkki 1983; Lappi 1986; Kilkki and Lappi 1987). Emphasis must be laid on the between-stand variation or the bias of the model in a certain stand. It is also emphasized that in the application of the models, any sample tree measurements can be used in the calibration of the models.

The sample tree data can be used to study, e.g., the following topics:

1. Taper curve
2. Taper curve change
3. Increment variation
4. Height-age site indices
5. Tree biomass
6. Quality of wood
7. Health of trees
8. The nutrient condition of the tree and its environment.

DISCUSSION

The final sampling procedure is still open. The sailing between Scylla of bias and Charybdis of error variance is difficult. This problem arises whenever the sampling probabilities are dependent on the variable (e.g., dbh) which is not used as a predicting variable in a model (Lappi and Bailey 1987). Derivation of unbiased models would be simple if the felled trees were sampled proportionally to the number of all trees. Then, however, data would comprise only few large trees. A partial solution may be found utilizing standing sample trees in addition to the felled sample trees and thus employing the whole measured tree data in estimation of the model parameters.

Our experience this far indicates that we maybe underestimated the measurement work. We have also got requests to increase the number of measurements per tree. Thus, it is possible that the final data will include less felled trees and more variables per tree than was planned.

One problem is caused by change of the tree foliage during the growing season. We try to cope with this problem by date registration.

Even though the cost of the data measurement is relatively high we hope to recover the cost manyfold by reduced sample tree measurements in future inventories. The benefits due to the improved knowledge of our trees are more difficult to evaluate but probably no less important in management planning calculations. Most probably the measurement of the felled sample trees will not stop at the end of this project but it will be an integral part of the future NFI's.

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INTERPOLATING CURRENT ANNUAL GROWTH FROM TWO DBH MEASUREMENTS

Colin D. MacLean and Charles T. Scott[1]

ABSTRACT. The current annual growth of inventory tally trees is frequently calculated by estimating the tree's volume 1 year ago and subtracting it from current volume. For remeasured permanent plots, the diameter at breast height (DBH) 1 year ago is interpolated between the current DBH and the DBH at the previous measurement. The estimated current annual growth depends on whether a constant rate of DBH growth or basal area growth is assumed.

To test various DBH growth assumptions, remeasurement data were analyzed from over 5,000 sample trees in western Oregon and Vermont, each with three DBH measurements spanning two inventory cycles. Using measured DBH growth from occasion 1 to occasion 3 as a base, the DBH of each tree at occasion 2 was estimated, using several DBH growth model assumptions. These estimates were then compared to the measured DBH at occasion 2. The best model assumption varied by species, stand age, and stand density, with no single model offering acceptable results for all conditions.

INTRODUCTION

Data from permanent plots provide successive measurements of DBH (diameter at breast height) at specific times. In a typical forest inventory, field plots are remeasured at regular intervals. If estimates of DBH are needed for an intermediate year, interpolation is necessary. The proper mathematical model for such interpolation, however, is not obvious.

The Forest Inventory and Analysis (FIA) projects of the USDA Forest Service face the problem of interpolation between DBH measurements each time they compile an inventory. Current annual growth is routinely calculated for each tally tree of each completed forest inventory. The usual procedure is to estimate the DBH and height of the tree 1 year before the current measurement; calculate the tree's volume 1 year ago, based on those estimates; and subtract that volume from the tree's current volume. Height growth is estimated from height-growth or site curves. These procedures were not examined in this study. Presently, most FIA projects assume that

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either DBH growth or basal area growth is a constant when they interpolate DBH for the previous year. If constant DBH growth is assumed, the DBH 1 year ago is calculated by subtracting the average annual DBH growth from the current DBH:

$$D_2 = D_3 - y_2(D_3 - D_1)/y_t, \tag{1}$$

where: D_3 = DBH at current measurement;

D_1 = DBH at previous measurement;

D_2 = DBH at an intermediate year (For calculating current annual growth, the intermediate year would be 1 year before the current measurement);

y_t = years between measurements; and

y_2 = years between intermediate estimate and current measurement (for calculating current annual growth, $y_2 = 1$).

If constant basal area growth is assumed, the calculation is:

$$D_2 = [D_3^2 - y_2(D_3^2 - D_1^2)/y_t]^{1/2}. \tag{2}$$

At a recent meeting of FIA mensurationists, these assumptions were questioned. They wondered whether DBH's at an intermediate year could be interpolated more accurately by assuming constant diameter growth or constant basal area growth. We decided to test both assumptions, using data from FIA plots that had been measured on at least three occasions. Knowing the DBH of each tree at the first measurement (D_1) and third measurement (D_3), we would estimate the DBH at the time of the second measurement (D_2) twice, once by assuming constant diameter growth (equation 1) and once by assuming constant basal area growth (equation 2). By comparing these estimates of D_2 with the actual measurements, we hoped to detect any systematic biases associated with either estimator.

A TEST OF EASTERN SPECIES

Our first test was based on a data set consisting of three successive DBH measurements of 2,367 trees that were part of an FIA inventory sample in Vermont. The period between surveys was 6-10 years for the first period and 9-11 years for the second. Nineteen species were represented--7 softwood species and 12 hardwood species. Diameter measurements were to the nearest 1/10th of an inch but are presented here in centimeters to be consistent with other study data; DBH at the second measurement was estimated twice for each tree based on an assumption of constant diameter growth (equation 1) and an assumption of constant basal growth (equation 2). In each case, the estimated diameters were subtracted from the measured diameters and a t-test performed on the difference. The results are shown in Table 1.

TABLE 1. A t-test comparison, by species, of two methods of interpolating between two successive DBH measurements, to estimate DBH for an intermediate year. Data are from three successive measurements of Vermont inventory plots.

Species	Interpolation method Basal area	 Diameter	Sample size
	------ t-value	------	
Softwoods:			
Balsam fir (Abies balsamea (L.) Mill.)	0.66	-4.25	103
White spruce (Picea glauca (Moench) Voss)	-0.48	-2.66	25
Red spruce (Picea rubens Sarg.	-3.15	-6.04	106
White pine (Pinus strobus L.)	3.02	-0.73	116
Northern white-cedar (Thuja occidentalis L.)	3.92	2.26	48
Eastern hemlock (Tsuga canadensis (L.) Carr.)	5.43	-0.41	310
Other softwoods	1.89	0.39	9
Hardwoods:			
Red maple (Acer rubrum L.)	6.49	1.63	255
Sugar maple (Acer saccharum Marsh.)	8.93	1.85	523
Yellow birch (Betula alleghaniensis Britton)	4.04	0.68	169
Paper birch (Betula papyrifera Marsh.	1.09	-3.00	172
American beech (Fagus grandifolia Ehrh.)	4.83	1.83	156
Ash (Fraxinus spp. L.)	5.57	2.42	53
Eastern hophornbeam (Ostrya virginiana (Mill.) K. Koch)	2.02	1.39	38
Bigtooth aspen (Populus grandidentata Michx.)	3.64	1.75	37
Quaking aspen (Populus tremuloides Michx.)	1.71	-2.16	62
Black cherry (Prunus serotina Ehrh.)	5.13	3.62	20
Red oak (Quercus rubra L.)	7.14	3.25	76
Other hardwoods	1.41	-1.37	89
All species	15.29	-0.12	2367

The constant diameter growth model performed best overall and best for 14 of 19 species and species groups. Although the DBH's of 5 species were underestimated, DBH estimates derived from this model were, on the average, unbiased. The constant basal area model, on the other hand, produced underestimates of the true DBH's. The estimated and measured mean DBH's for the 2,367 sample trees were:

Projection or measurement method	Mean DBH at occasion 2
	--cm--
Constant basal area growth	27.585
Constant DBH growth	27.954
True measured DBH	27.950

Although these data support the assumption of constant DBH growth, that assumption seems to contradict what is known about how trees grow: DBH growth is known to culminate at an early age and then decline sharply (Assmann 1970). Although no effort was made to correlate growth with climatic cycles, we recognized that such cycles could skew the results. The first measurement period was a time of drought in Vermont, for example, but rainfall was normal during the second period. And the five species for which the constant basal area growth assumption gave better results grew at higher elevations where growth loss and heavy mortality have been reported, with atmospheric deposition suspected as a cause. In any case, we felt that DBH growth should slow down as the tree ages. For this reason, we decided to examine additional data from another geographic region.

A TEST OF PACIFIC NORTHWEST SPECIES

The two interpolation assumptions--constant diameter growth and constant basal area growth--were retested against remeasured tree data from a recent FIA inventory of western Oregon. Over 2,800 trees were available. The first remeasurement period was 11-15 years and the second was 9-12 years. The results are shown in Table 2.

TABLE 2. A t-test comparison, by species, of two methods of interpolating between two successive DBH measurements, to estimate DBH for an intermediate year. Data are from three successive measurements of western Oregon inventory plots.

Species	Interpolation method: Basal area	Interpolation method: Diameter	Sample size
	---- t-value ----		
Softwoods:			
True fir (Abies spp. Mill.)	0.65	-2.66	142
Port-Orford cedar (Chamaecyparis lawsoniana (A Murr.) Parl.)	1.29	0.10	21
Incense cedar (Libocedrus decurrens Torr.)	2.05	.04	49
Sitka spruce (Picea sitchensis (Bong.) Carr.)	2.24	-1.48	61
Pine (Pinus spp. L.)	-0.57	-7.62	76
Douglas-fir (Pseudotsuga menziesii (Mirb.)Franco)	7.77	-11.25	1540
Western redcedar (Thuja plicata Donn ex D. Don)	2.98	-0.96	93
Western hemlock (Tsuga heterophylla (Raf.)Sarg.)	-0.12	-2.95	237
Hardwoods:			
Red alder (Alnus rubra Bong.)	-8.08	-11.39	260
Other hardwoods	-4.42	-7.84	374
All species	3.12	-18.04	2815

The western Oregon test failed to establish that either model was superior. In fact, hardwood DBH growth was so much slower in the second remeasurement period than the first that both models underestimated DBH at the second measurement. Neither model fit Douglas-fir or Sitka spruce DBH growth well either. In both cases, the DBH growth model underestimated the second-measurement DBH's and the basal area growth model overestimated them. DBH growth was nearly constant for three of the remaining six species tested, and basal area growth was nearly constant for the other three.

Our next step was to sort the trees into 10-cm DBH classes, 10-year age classes, and stand density classes. Surprisingly, density seemed little related to changes in DBH growth--at least during the 20- to 25-year period we examined. The goodness of fit was, however, correlated with DBH and age, with diameter apparently serving as a proxy for age. When conifer species were sorted into DBH classes, differences between species largely disappeared, but differences between DBH classes remained, with basal area growth constant for small trees and DBH growth nearly constant for large trees. A closer look suggested that DBH growth was linear, provided that DBH was raised to a power, but that the appropriate power function varied both with species group and DBH class. Thus, equation (2) was modified to read:

$$D_2 = [D_3^x - y_2(D_3^x - D_1^x)/y_t]^{1/x}, \qquad (3)$$

where: x is a coefficient.

Thus, by trial and error, we selected the power functions that provided unbiased estimates of the occasion 2 DBH's measured for the western Oregon data set. The results are shown in Table 3.

TABLE 3. A comparison, by species group and DBH class, of estimated and measured DBH at the second of three successive measurements using a power function. Data are from western Oregon inventory plots.

Species group and occasion 1 DBH class	Best model	Mean DBH, second measurement		Root mean squared error	Sample size
		Measured	Estimated		
centimeters		----------centimeters-----------			no. trees
Softwoods:					
< 20	$D^{1.8}$	24.85	24.85	1.6	369
20-44.9	$D^{1.7}$	39.80	39.81	1.3	939
≥ 45	$D^{1.2}$	87.50	87.48	1.2	873
Hardwoods:					
Red alder	$D^{4.0}$	39.97	39.95	1.2	260
Other species:					
< 45	$D^{4.0}$	30.41	30.43	0.8	299
≥ 45	$D^{2.5}$	65.51	65.54	1.1	75

In western Oregon, hardwood DBH growth rates seem to decline markedly with increasing size, and conifer growth rates decline less severely. Except for red alder--a short-lived tree--the growth rates of trees under 45 cm in DBH declined more rapidly with increasing DBH than did those of larger trees. The change at 45 cm is an abrupt one. Why this should be is not clear. Perhaps it may relate, in some way, to the stand history of trees in western Oregon.

CONCLUSIONS

In general, the western Oregon data followed the pattern described by Assmann (1970). Although the culmination of diameter growth cannot be determined because of the truncated data set (no trees smaller than 12.5 cm) and the relatively long period between measurements, DBH growth rates did decline at a decreasing rate as the trees grew larger. Assmann suggests that the curve should be steeper for light-demanding species than for shade-tolerant ones. This rationale does not entirely explain the sharp difference between conifers and hardwoods.

The rapid decrease in DBH growth noted in the western hardwoods is not evident in Vermont data set. In general, differences between species in DBH growth patterns seem much greater in Vermont than in western Oregon. Although the effect of size or age on the rate of change in DBH growth was not examined in the Vermont data, for all the differences between species to be attributable to differences in size-class distribution seems unlikely.

How then, should the DBH's of tally trees on permanent plots be estimated for years when no measurements were taken. Consistently unbiased estimates cannot be obtained by assuming either constant DBH growth (D) or constant basal area growth (D^2). Although DBH growth is known to culminate at an early age and then decline, the rate of that decline appears to vary with species, tree size, and possibly geographic location. We suspect that it also changes with changing stand density, although we failed to find such a correlation in this study. The data presented in Table 3 probably provide reasonable guidelines for use in western Oregon and possibly western Washington. For other regions, local studies are needed to define the relationship between DBH growth, species and tree size or age.

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INFORMATION MANAGEMENT TO SUPPORT DEVELOPMENT OF GROWTH MODELS FOR MULTI-PURPOSE TREE SPECIES

Dietmar W. Rose and Luis Ugalde[1]

ABSTRACT. The development of growth prediction models for multi-purpose tree species (MPTS) requires large amounts of experimental data. While much experiment-based information on MPTS systems exists world-wide, this information cannot be readily accessed or be exchanged because no uniform standards for measurements have been established and key environmental information is frequently not recorded. A data-base including minimum data set definitions that will facilitate the efficient exchange and transfer of information on forestry and MPTS research among scientists and regions of the world is being developed with the financial support of the Kellogg Foundation at the University of Minnesota in cooperation with the Fuelwood Project at the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) in Costa Rica. This data base for MPTS with experiment data from more than 10,000 plots for 6 Central American countries could become the prototype for similar systems in other parts of the world.

INTRODUCTION

MPTS research is difficult to conduct due to the number of species and the multiple products involved in these systems. Trees in such systems are used for the production of posts, fodder, fruits, fuelwood, and other products and serve to enhance the production of agricultural crops and lifestock. The development of growth and yield model for MPTS will require the collection of large amounts of information for different MPTS production systems in different growth environments. No single organization has the resources to collect sufficient data to quantify all major MPTS production systems. It will, therefore, be necessary to develop data collection standards such that data from many sources can be pooled for improved modeling efforts (Rose and Cady 1987). Beyond this, MPTS field experiments need to be coordinated to avoid duplication of effort and to cover as wide a range of species, sites, and treatments as possible. This coordination will require establishment of standards of measurements, of minimum data sets required for modeling, and efficient storage, organization, and retrieval of data.

GROWTH MODELLING FOR MPTS

Yield tables have been the foresters most valuable tool for managing forests. They are the basis for decisions on rotation age and for prediction of the yield to be expected at a specified age. Normal yield tables, based usually on time-series data, require great inputs of time for development, especially for the long rotations of temperate forests. To overcome the problems of the normal yield tables, two other types of yield tables have become the standard tools for foresters in many parts of the world, the variable-density yield table and the managed-yield table. The former describes the yield of a stand as a function of age if stand basal area is reduced through thinnings to some fixed level at periodic intervals, the latter describes stand development for specific management regimes imposed on a stand. Much effort is now going into the development of more flexible stand-growth and individual tree-growth simulation models for the most important commercial covertypes and species. An example of such an individual tree-growth model is STEMS (USDA Forest Service 1979).

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Kimmins (1985) reviewed the major approaches to the scientific investigation of forest yield and growth. The empirical, historical-bioassay approaches (all yield tables described above fall into this category) are becoming less and less acceptable because of their inability to make predictions of future production with changing environmental conditions and forest management systems. Newer approaches need to rely on an understanding of the biological and environmental determinants of forest production, and not only on records of past plant growth.

Bio-assay models will continue to be useful for short-term yield predictions where time required to establish the bio-assay is not too long. Parallel to this approach, yield or productivity should be related to either simple or complex environmental gradients or to individual environmental factors, e.g., temperature, precipitation, temperature and precipitation combined, actual evapotranspiration, and length of vegetation period. Within an area of relatively uniform climate, soil moisture and soil fertility are gaining increasing use in the prediction of site-yield potential. Other soil, topography, and vegetation parameters should be examined for their potential as yield predictors (Kimmins 1985).

It is apparent that MPTS growth modeling will require such new approaches. Growth and yield models are needed that describe the interaction of stand management and environment. The establishment of coordinated experiments world-wide should provide an opportunity to make great strides towards growth and yield models that can become useful beyond the sites in which the experiments take place. These environmental models which relate growth and yield to environmental factors such as soil, site, and climate would represent a major advance over models developed for temperate forests.

The key enduses of growth and yield models for MPTS are:

1) to match species and sites not only for survival but in terms of performance, i.e., total biomass production or component production,
2) to quantify the trade-offs between management systems, e.g., fuelwood versus fodder production, or the combination of different products,
3) to facilitate MPTS technology transfer beyond sites of experimentation.
4) to provide production functions for economic analysis of MPTS production systems.

SITE DESCRIPTION

Any information system dealing with a biological production system, e.g., agriculture or forestry, requires an environmentally or geographically based referencing system. Without the latter, scientific information on performance of specific plant production systems cannot be compared or transferred between locations. An environmental data base has the function of relating different kinds of information in forestry, agriculture, and agroforestry research to a common basis of environmental information. For example, soil taxonomy has provided the common language for communicating soil and climatic information to scientists in widely separated countries (Silva and Uehara 1985). To overcome the enormous obstacles of time and money needed to develop predictive models for the large number of MPTS production systems, it is essential that research experimentation is coordinated and that reseach findings are shared. Only by pooling data from well coordinated experiments will it be possible to develop environmental growth and yield models for major MPT species and systems within the next decade. Several environmental models that attempt to integrate climatic conditions with existing vegetational patterns exist. The underlying hope in using such models is that important agricultural and forestry-crop cultural techniques might be shifted from one part of the world to another with a predictable measure of success. A general discussion of several of these models can be found in McFadden (1984). The AID funded fuelwood project at CATIE is using the system developed by L.R. Holdridge (1947) designed to determine world-wide plant formations from simple climatic data (Ewell and Whitmore 1973). The experience of the Benchmark Soils Project suggests that propagation and cultural technology associated with agronomic crops can be expected to be more easily transferred within than across climatic regions (Silva 1985). Some mathematical models could be tested to describe the relationship between soil, climate, and management variables, and forestry or agricultural crop yields. Such models may be used to analyze, expand, and transfer MPTS technology. Cagaun et al. (1982) reported an application of the Benchmark Soils System in agroforestry and fuelwood production. They also present information on procedures used to match tree requirements with environmental conditions in new sites and present a case history as an example. The information required by this system would be difficult to collect in forestry applications.

A major drawback to use of the major environmental classification schemes reviewed according to McFadden (1984) is that they rely on climate/climax vegetation associations that existed at the time the model was developed. In some parts of the tropics today, deforestation has so changed existing climate and soil fertility that it is highly unlikely that the original climax vegetation could ever be achieved again. Consequently, predictions should not be based only on these environmental classifications, but also on the actual current measurements of key environmental variables such as soil, temperature, and rainfall that are also part of these models. Comparison of quantitative models among life zones might prove interesting. These comparisons would also show whether ecological classification schemes are sufficient for prediction purposes.

Soil scientists have recognized that interactions between soil characteristics, crop requirements and management practices could be integrated and could provide an effective basis for knowledge transfer, especially when soil taxonomy is included in the equation. It might prove more difficult for forestry research because usually much larger areas are involved. Soil taxonomy is the system of classifying soils that was developed by the Soil Conservation Service (Soil Survey Staff 1975). It is basically an American system but is gradually becoming an internationally accepted especially by soil scientists in the Third World. This nomenclatural system provides a uniform basis for communicating information about soils and their management. There are 6 major soil categories but the soil family is the category that relates soil properties to management and manipulation of soils for specific uses. It also includes most of the information needed to transfer agrotechnology among similar classified soils.

A DATA BASE FOR MPTS MODELING

Data bases become useful only if they can directly support decision making (Rose and Ugalde 1985). Data recorded in the field either must directly provide the necessary information for decision making or the variables needed for development of models that can support decision making. Data are transformed into information (outputs) for decision making utilizing scientific methods and models, e.g., simulation, statistics, and economics. It is necessary to understand the relationship between key dependent and independent variables before setting up experiments (Rose and Cady 1987). Once these outputs are known, a minimum data set needs to be developed, i.e., the variables that need to be observed and measured in the field. This paper attempts to provide the information on possible modelling efforts that are consistent with the minimum data set that need to be developed to faciliate pooling of data.

MINIMUM DATA SETS FOR MPTS MODELING

A clear frame of reference is needed to identify the gaps in current information on MPTS and associated growth and yield models and to coordinate the efforts that could fill these gaps in the shortest possible time through coordination and cooperation among scientists. Uniform standards for implementing MPTS experiments are being established to permit global exchange and transfer of scientific information on MPTS. These standards and minimum data sets are being developed in close coordination with scientists to ensure production of useful information and to gain acceptance of these standards. Scientists also need to coordinate their experiments to cover a wide range of sites including the extreme sites for which typically information is especially scarce. This coordination will ensure that research focus on the most important species and management approaches.

Detailed technical guides for the establishment, measurement, analysis, and model development of multi-purpose tree species (MPTS) production systems need to be developed to permit global exchange and transfer of scientific information on MPTS.

MPTS PRODUCTION SYSTEMS

The development of minimum data sets, appropriate field forms, and field measurement guides for plantation experiments is relatively easy because much experience exists worldwide in plantation forestry. Stand and individual tree growth modeling techniques that work in temperate zones of the world can also be applied in the tropics. Once some models have been successfully developed and tested, calibration of model parameters might permit using such a standard model type in other regions. Using existing model shells from temperate zones such as the STEMS model would shorten model development time considerably.

Natural forests present a different problem for quantification because often the history of the stands, i.e., origin and previous management interactions are not known, and the stands often are mixed stands of several species. Growth modelling is, therefore, extremely difficult and often simply not possible. Stem analysis, a technique useful where trees put on distinct growth rings in accordance with a growing and non-growing season are usually not possible in MPTS of tropical areas. In natural forests, it is normally more difficult to find homogeneity to apply different treatments compared with pure plantations. Also, prescribing treatments that are biologically sensible and statistically adequate may become difficult, certainly if knowledge of biology is weak. Care is needed to ensure that the treatments applied to mixed stands can be applied consistently and uniformly.

Agroforestry systems are the most difficult MPTS system to quantify. The difficulty arises not only from the multiple outputs produced in such systems, but more from the numerous combinations of trees, agricultural crops, and animals that make it less likely that repeated experiments can be found in many environments. To coordinate such trials, scientists need to agree to work on some more widely accepted and sometimes simpler agroforestry systems. Some experience already exists for living fences, windbreaks, and individual trees in pasture in the Central American Fuelwood Project (Salazar and Rose 1984), but ver little is known concerning the interaction of trees with agricultural crops.

MEASUREMENTS REQUIRED

One of the features of MPTS production systems is that they produce a variety of outputs depending on the management objectives. Wood products typically include not only the commercial stem of a tree, but often branches are cut into posts and fuelwood, even fine branches serve as a source of energy, leaves and the finest portion of branches might be used as cattle feed, and seeds and fruits from the trees might be an important source of nutrition for local populations. Field techniques have to be designed to measure these different outputs and related variables so that predictive and other models can be developed to support decision making.

While the quantification of the commercial stem of trees on the basis of tree diameter, height, and some measure of form such as taper (ratio of diameters at different heights on a tree) or sectioning of trees into various parts including diameters of the parts and section length is well established, the quantification of other components of trees is not. The reason is that these other components typically have not played a very important commercial role. The fuelwood project is developing the methodology to quantify major components of some MPTS production systems that are used by rural populations to facilitate the comparison and ranking of alternative tree species and production systems.

One of the questions that is difficult to answer for these non-traditional products is what variables to measure in the field in order to develop prediction models for the output such as fuelwood, foliage etc. Initially, it will be necessary to measure a number of variables that later may turn out to be unnessecary. Until such models have been developed and have been tested and found to be applicable, projects would theoretically have to measure many variables that might be useful in modeling of the desired output. Practical considerations dictate, however, the selection of fewer variables. These relations between variables may need to be established for each major tree species as these relations may well vary between species.

Because of the high cost of measurements, projects also need to be familiar with and emphasize proper statistical sampling procedures. While frequently individual trees and its components need to be quantified, selection of representative trees need to be made and techniques such as ratio and regression estimators that take advantage of correlations between variables that are difficult to measure and variables that are easily observed should be used to improve on the precision of estimators. For tree characteristics not measured on every tree or on every plot such as crown ratio, it would be necessary to derive local or regional prediction models from subsamples. Such models would predict variables that are difficult to measure from predictor variables that are included in the minimum data set for each experiment plot.

APPROPRIATE MODEL TYPES FOR MPTS

Much can be learned from the modelling experience of temperate forests and much of the methodology is applicable to MPTS modelling efforts. An excellent summary of growth modelling methodology is contained in Clutter et al. (1983). It describes the most common methods for constructing site index curves and growth and yield models for basal area and volumes of trees and stands. Application of these methods for constructing growth and yield models for MPTS requires a word of caution, however. Management and modelling problems faced by foresters in the tropics are considerably more complex. Because MPTS systems produce multiple outputs that need to be quantified, growth and yield models need to be developed for each individual component. Furthermore, interdependencies exists among these individual components, i.e., increased production of one may reduce the production of another. Because of these interdependencies, many more management regimes need to be examined than in temperate forests. Management treatments imposed may represent a compromise between producing sufficient biomass and achieving some defined level of another output. Additionally, there are potentially enumerable MPTS while temperate forests only contain a few commercial species. The only advantage of MPTS over temperate species is that rotations are typically much shorter. This advantage is counteracted on the other hand by the potential of many MPTS to coppice which introduces further complexity into growth and yield modelling. The quantification of growth and yield of agroforestry systems involving enumerable mixes of tree species, annual plants, and animals is the ultimate challenge to the growth and yield modeler.

The development of growth and yield models for MPTS can benefit somewhat from the modeling experience and the approaches of the temperate forests especially for plantation forests of single or mixed species. At the same time the errors that were made in their development can be avoided. Measurements should be made so that modellers are not locked into one specific product or utilization standard, i.e., it should be possible to quantify biomass of any part of the trees in the experiment and to enable development of functional relations between difficult to measure characteristics such as tree form or crown characteristics with more easily measured variables such as dbh and height. Measurements obtained from individual trees should be accessible in the data base if development of individual tree-growth models is desired.

For temperate-zone forests often plot data were lacking for ages less than 10-20 years. For that reason, few models of the establishment phase of forests exist and relatively little work has been done on modelling ingrowth. Models selected to best describe growth and yield of temperate tree species may, therefore, not always be the most suitable for MPTS with short rotations and for which the early growth periods have great significance. The behavior of and the relationships between some variables might turn out to be quite different than in temperate forests. Ingrowth should be less of a problem in MPTS research as all trees regardless of size will be included in the measurements throughout the measurements.

Models for the quantification of yields of wood and other products will most likely be regression-type models. Polynomials and nonlinear models can be found in the literature (e.g., Clutter et al. 1983). A large number of possible model forms has been tested sufficiently so that they may be applied to MPTS outputs. What is new for MPTS is the quantification of these outputs via appropriate measurement procedures. The sheer number of MPT species, treatments, and MPT outputs make the development of descriptive summary tables and graphs by key environmental and management factors the first priority to begin to understand key relationships among factors.

Prediction models for MPTS outputs can be developed for stands or individual trees. Individual tree-based forest-stand growth models represent a powerful approach to predicting forest growth, yield, and response to treatment (Dudek and Ek 1980). Individual distance-independent tree-growth models such as STEMS (USDA Forest Service 1979) might represent a useful approach to model individual trees in pasture and in silvopastoral research. These models are based on estimates of potential growth of open-grown trees (without competition) and the modification of this growth potential by some modifier function which characterizes competition through descriptors such as crown ratios and by modelling mortality. Such a model once calibrated can handle many spacing patterns or other factors that influence individual tree characteristics. These models are quite flexible, and require individual tree observations for the range of growing conditions (environment and treatments) desired for prediction purposes. Existing programs could be modified to MPTS systems. A modelling methodology still needs to be developed for the modifier function since the current minimum data set does not include characterization of the tree crown. Mortality estimates might be easier to obtain because of the short production periods of MPTS systems.

Care needs to be exercised when these model types are being adopted to MPTS systems. In individual tree-growth models, the many management treatments that represent different production goals such as maximum biomass production or achievement of some defined level of multiple outputs adds to the complexity of modeling growth growth potential without competition.

Development of operational simulation models that can predict growth and yields of the individual components of MPTS systems over a wide range of environments and treatments will require large amounts of data that cover the full range of sites and treatments encountered in practice. The minimum data set of the CATIE prototype offers the potential for the development of such simulation models. In the development of environmental growth and yield models, climate data will play an important role. The availability of long-term historic or actual weather data from the experiment will provide opportunities to develop environmental simulation models for MPTS that up to now have not been available. The best hope for such models is that many of the ongoing experiments can be captured in the format of the current minimum data set. Unfortunately, for the majority of ongoing MPTS experiments in the world, climatic observations during the experiment and on the experimental site are impossible to obtain. Environmental simulation models will have to be developed more likely based on historical climate information obtained from the nearest meteorological station.

If only historical climate data from the nearest weather station are used, tree response cannot be modelled as precisely as when actual weather observations during the growth experiment on the site are available. If weather station data are used exclusively, the possibilities of fitting functions to describe climate between weather stations via smoothing and other techniques need to be considered. While such smoothing is being applied successfully for temperature, it is apparently more difficult for rainfall. Large variations can exist over fairly short distances. In most cases, differences in average seasonal rainfall distribution between locations should not represent a major problem as long as weather stations are fairly close and are not situated in radically different elevations and topographies from the growth experiments.

CONCLUSIONS

Development of growth and yield models for MPTS represents a difficult task. It will require a lot of basic research. Only the establishment of scientists' networks for research coordination and data sharing offers some hope that such growth and yield models can be developed relatively soon. The establishment of such a network for Latin America is the content of a recent proposal presented at a IUFRO conference in Peru (see Rose and Ugalde 1987). Establishment of a data base of MPTS experiments will be necessary to model growth and yield of MPTS production systems. Through the development and acceptance of standardized procedures, MPTS experiments can be coordinated to avoid duplication of effort and to emphasize species, sites, and treatments that have not been adequately covered. Information gained from these experiments can be easily transferred and be shared among cooperating scientists. An established MIS will permit the retrieval of any or all information maintained in the data base. Information retrieved from the data base can identify priorities for data collection not currently adequately covered and avoid generating information that already exists. The ease of transferring information will facilitate planning of projects that will complement existing information.

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FOREST INVENTORY AND ANALYSIS NEEDS FOR A GROWTH PROCESSOR

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ABSTRACT. The Forest Inventory and Analysis units at the experiment stations within the USDA Forest Service conduct periodic surveys of the forest lands of the United States. The FIA units must then project the forest resource; they must have appropriate growth projection modelling systems for all species and stand conditions. Currently, no such system or collection of systems exists that covers the full range of conditions encountered. The growth processor should be applicable at the state or regional level and at the individual stand level. The growth processor also should be an individual-tree, distance-independent system containing several subsystems including growth, mortality, removals, regeneration, and non-tree vegetation.

INTRODUCTION

The Forest Inventory and Analysis (FIA) projects at the experiment stations within the USDA Forest Service conduct periodic surveys of the forest lands of the United States. Results of these surveys are used to develop estimates of current forest area and volumes and to report estimated trends in both forest area and volume. The FIA projects also use the periodic survey data to project the forest resource based on various assumptions about the future. To do this, they must have appropriate growth projection modelling systems for all stand conditions and species encountered. Currently, no such system or set of systems exists that covers the full range of forest conditions.

In this paper we, in collaboration with all FIA projects, propose that projection systems be developed for all forest conditions as part of a coordinated effort between organizations involved in forest growth modelling. The USDA Forest Service has prepared a National Growth and Yield Development and Implementation Plan that addresses much of this problem. However, we describe desirable components and characteristics of a growth processor to ensure that all FIA modelling needs are met. Such models would have wide applicability both in and outside the Forest Service.

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PAST MODELLING EFFORTS

Most forest growth modelling has focused on specific species or forest types. Typically, such modelling efforts have addressed a rather narrow set of objectives, such as the growth and yield of old-field loblolly pine. For obvious reasons the greatest emphasis has been placed on managed stands and commerically valuable species, such as Douglas-fir or the southern yellow pines. In the Forest Service, for example, the experiment stations each have Timber Management Research projects charged with developing growth processors specific to the species of interest in their region. In the Douglas-fir subregion of the Pacific Northwest, heavy reliance is placed on even-aged stand simulation models such as DFSIM (Curtis and others 1981). Although such models work well in managed stands and in well-stocked even-aged natural stands, they were not intended to be used to project natural stands with multiple age classes, mixed species, or a history of partial cutting. Thus, such models fall considerably short of meeting FIA projection needs.

Two projects have developed growth processors that are applicable to most species and stand conditions over a broad region. PROGNOSIS (Stage 1973) was developed for use in the Intermountain region and STEMS (Belcher et al., 1982) was developed for the Lakes States. The need for regional growth processors has resulted in a Central States version of STEMS (Shifley 1987) and ongoing research into versions of TWIGS (a variation of STEMS) for the Northeast (Hilt et al., 1987) and for the Southeast.

Several versions of PROGNOSIS are being developed. The effort is being coordinated by the Forest Service's Mensuration and System Development Unit located in Fort Collins, Colorado.[1] PROGNOSIS is now calibrated for use in southeast Alaska, Montana, Idaho, Wyoming, Utah, and sizable portions of eastern Oregon, Washington, and California. Versions are also being developed for use in Douglas-fir-tanoak communities of northern California, Sierra westside of California, and East Cascades of Washington. Both the STEMS model and the PROGNOSIS model have many components and characteristics that are needed by the FIA projects.

DESIRABLE GROWTH PROCESSOR CHARACTERISTICS

The primary need of a growth processor is to project the forest resource into the future, thus updating the survey. In addition, various management strategies must be applied based on assumptions about the future. As a result, the growth processor should be an individual-tree, distance-independent system. Individual-tree systems provide updated "tree lists" with which existing software can be used to provide survey projections. If stand models are used, they must generate tree lists by diameter class. Individual-tree models also provide for modelling tree quality. Distance-independent models allow users who do not record tree distance and azimuth to use the system.

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[1] Personal communication with Ralph Johnson, USDA Forest Service, Ft. Collins, Co.

The growth processor should be applicable at the state or regional level as well as at the individual stand level. Most growth processors are developed for a specific forest type within a small geographic area. Models should be applicable to all forest conditions in entire states or regions, such as the Lake States.

The system should provide for the following eight modelling components:

1. Diameter at breast height (DBH) increment
2. Crown ratio (or other available measure of vigor)
3. Merchantable height increment (for estimating current net volume)
4. Quality increment (for estimating current net volume)
5. Regeneration
    a. Plantations
    b. Natural (regeneration assuming no overstory)
    c. Incremental all-age management (regeneration assuming an overstory)
6. Mortality
    a. Endemic
    b. Catastrophic (for optional use)
        - site specific (e.g., tornados or local flooding)
        - not site specific (e.g., regional drought)
7. Removals based on:
    a. Silvicultural guides
    b. Area/volume control
    c. Past cutting history
    d. Economic considerations
    e. Wildlife and other constraints as needed
8. Non-Tree vegetation (for habitat modelling)

The DBH Increment models are developed using remeasured plots. Crown ratio is used as an independent variable to predict DBH increment but must also be predicted over time. The merchantable height models can project either merchantable height directly or height increment. The quality increment models provide estimates of the change in the portion of the tree that is rough or rotten and of the change in tree quality (grade). The regeneration component provides for ingrowth and for artificial and natural regeneration, which includes regeneration after harvest. The mortality component is developed using remeasured plots and provides for endemic (expected or "normal") mortality as well as local and regional catastrophic mortality. The removals component provides for a variety of management strategies including methods used in practice. The non-tree vegetation component is less well-defined due to the regional nature of habitat modelling.

The growth processor will require the following inputs:

1. Tree list (defined below)
2. Overstory stand age
3. Site quality
4. Miscellaneous information required by individual components
5. Weather
6. Projection interval

The tree list should contain the following:

1. Species
2. DBH
3. Tree status (live/regeneration/dead/cut)
4. Tree quality class
5. Height
6. Crown ratio
7. Log grade
8. Percent cull
9. Tree expansion factor (e.g., number of trees per acre)
10. Diameter increment--current annual (observed or predicted)
11. Crown position (optional)

The growth processor will produce the following outputs for each projection interval:

1. Updated tree list (previously defined)
2. Overstory stand age
3. Site quality
4. Projection interval

This output can then be used as input to the next projection period and for computation of survey estimates for each projection period.

CONCLUSIONS AND SUMMARY

The FIA projects are required to provide detailed projections of the forest resource for all forest lands in the United States. No growth projection systems or collection of systems satisfies this need nationally. Some systems are available for particular regions. We are encouraged by the National Growth and Yield Development and Implementation Plan, and we hope that each of the regional plans (e.g., Hilt et al., 1984) will be re-evaluated based on our recommendations. Not only are these models needed by FIA, they are also needed by the National Forest System, other federal agencies, state agencies, forest industry, and private organizations.

The desirable growth processor components and characteristics presented were developed by representatives from the FIA projects with input from representatives from the National Forest System. We believe that these characteristics will also meet the National Forest System needs as well as the needs of users outside the Forest Service. We urge that modellers seriously consider the use of individual-tree, distance-independent models that include the eight components described. This does not mean that a single set of model forms must be adopted nationally. Individual growth processor components can differ substantially in methodology. However, the inputs and outputs must meet the criteria described.

We recognize that this effort will require additional funding. If the various independent modelling efforts can be coordinated, perhaps a cooperative effort can result in the models we all need.

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A MANAGEMENT-INFORMATION SYSTEM FOR MULTI-PURPOSE TREE SPECIES RESEARCH IN CENTRAL AMERICA[1]

Luis Ugalde Arias and Dietmar W. Rose[2]

ABSTRACT. A management-information system (MIS) on multi-purpose tree species (MPTS) research is now operational at the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) in Costa Rica. The microcomputer-based MIRA (Manejo de Información sobre Recursos Arbóreos) system has been developed with the financial support of the Kellogg Foundation at the University of Minnesota in cooperation with the Tree Cropping and Fuelwood Production (MADELEÑA) Project at CATIE. This system represents the pioneering work in use of data base and MIS technology in the tropical regions of the world for application of silvicultural research. It is also the first successfully applied scientific study with standardized data collection procedures carried out cooperatively by six countries of Central America. This effort could become the prototype for similar networking efforts in other parts of the tropics.

INTRODUCTION

Since 1980 CATIE - with the economic support of USAID's Regional Office for Central American Projects, and with additional support in funds and personnel of six Central American nations - has been carrying out a forestry research project in MPTS. The MADELEÑA Project is being coordinated and implemented through agreements between CATIE and the national institutions charged with forestry research in Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica and Panama.

The MADELEÑA project deals with one of the most urgent problems in Central America and other tropical area of the world, the production of fuelwood for the rural poor who depend on this form of energy for cooking and heating almost exclusively. To reach its objectives, the project already has identified critical areas in all countries of Central America, and since 1980 has initiated a large number of formal and demonstration units for testing fuelwood species and management systems (CATIE 1986). Figure 1 shows the current distribution of experimental areas in Central America.

Experimental MPTS data have been collected in six Central American countries over a wide range of environmental and site conditions, and a variety of MPTS production systems. The project has worked with over 150 MPTS species, of which 15 have been identified as major species for more intensive experimentation. To help organize the entry and retrieval of all relevant information generated by the project, the

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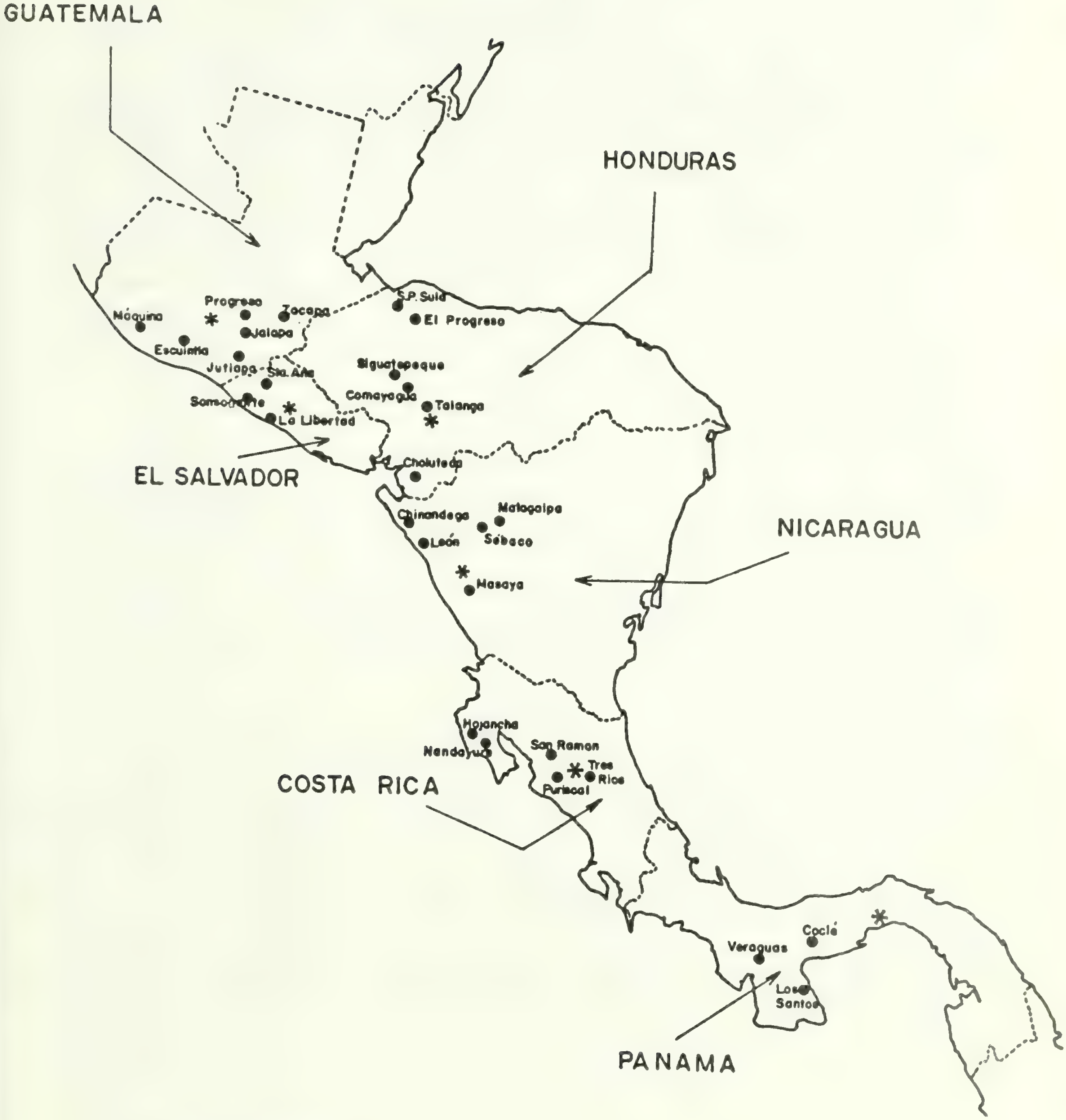

* Country capital
o Experimental sites

Figure 1. Experimental sites distribution in Central America.

need for development of an MIS that combines silvicultural, physical, climatic, social, and economic information was identified (Rose 1985; Ugalde, Rose and Salazar 1987).

JUSTIFICATION FOR A DATA BASE

Data bases become useful only if they can directly support decision making (Rose and Ugalde 1985). To make appropriate management decisions involving MPTS requires the development of growth and yield model. Such models are based on large amounts of information for different MPTS production systems in many different growth environments. The difficulty in conducting MPTS research is enhanced by the number of species and the multiple products involved in these systems. Trees in such systems are used for the production of posts, fodder, fruits, fuelwood, and other products and serve to enhance the production of agricultural crops and livestock. No single organization has the resources to collect sufficient data to quantify all major MPTS production systems. It was, therefore, considered necessary to develop common data collection standards such that data from all Central American countries could be pooled for improved modeling efforts.

Kimmins (1985) reviewed the major approaches to the scientific investigation of forest yield and growth. The empirical, historical-bioassay approaches are becoming less and less acceptable because of their inability to make predictions of future production with changing environmental conditions and forest management systems. MPTS models need to rely on an understanding of the biological and environmental determinants of forest production, e.g., temperature, precipitation, and site and soil characteristics (Rose and Ugalde 1987a). Growth and yield models are needed that describe the interaction of stand management and environment.

DATA BASE DESIGN

In order to manage all the information collected, the MIRA (Manejo de Información sobre Recursos Arbóreos) System is one of the fundamental components of this second phase of the MADELEÑA Project. MIRA is initially being developed through an agreement between CATIE and the University of Minnesota with support from the Kellogg Foundation. The MIRA System includes the information generated by field research plots from both the current Project and its precursor at CATIE. The design reflects the most important aspects of the environment or real situation in which the project work is being carried out. Initially, the MIRA database is being implemented with silvicultural information on MPTS, seeds, soils, site characteristics and meteorological information. Later, as other Project research activities begin to require database support to manage data on socioeconomic factors and training, these aspects will be integrated into the database as well. MIRA's database is also designed to store data from new experimental designs, both those of the MADELEÑA Project and any others for which participating nations may choose to apply this computer tool. The design will permit the system to provide relevant information for different users: the farmer, the extensionist, national and international researchers, and national planners in the region.

Data recorded in the field or derived information either must directly provide the necessary information for decision making or the variables needed for development of models that can support decision making. Data are transformed into information (outputs) for decision making utilizing scientific methods and models, e.g., simulation, statistics, and economics. The outputs to be developed by research need to be clearly identified before identifying the variables that need to be measured for development of predictive and/or explanatory models. It is necessary to understand the relationship between key dependent and independent variables before setting up experiments (Rose and Cady 1987). Once these outputs are known, a minimum data set needs to be developed, i.e., the variables that need to be observed and measured in the field. An information system must, therefore, begin by defining the "necessary and sufficient" conditions for the data, and it should also specify the requirements of its structural format.

An entity-relationship model of the MIRA System's underlying data base was developed to assure an effective structure for all the Project's needs. At this time the data base is in operation on microcomputers in a prototype form. All the Project's silvicultural data through the beginning of 1987 has been transferred into the data base, as well as a large part of the data for soils, seeds, site description, species description, and temperature and rainfall information. As these components are completed other components will be added and the construction of models showing the predictive relationships to be found in this vast quantity of data will be added to those now in existence.

The system is designed to handle the various types of production systems that are encountered in MPTS, from natural stands, plantations, to some agroforestry systems. One of the features of MPTS production systems is that they produce a variety of outputs depending on the management objectives. Field techniques have been designed to measure these different outputs and related variables so that predictive and other models can be developed to support decision making. Agroforestry experiments represent the most difficult aspect in terms of quantification and the development of minimum data sets among the MPTS systems. The difficulty arises from the multiple outputs that are typically produced (Ugalde 1979). The numerous combinations of trees, agricultural crops, and/or animals that make up such systems, and the small number of experimental replications.

The hierarchy that has been established for identifying an experiment or demonstration plot data for the prototype data base being developed for the fuelwood project at CATIE is shown in Figure 2 below:

```
Country                                         <---
     Site                                          |
          Compartment=Lot                          | Experiment
               Replication                         |
                    Plot=Treatment                 |
                         Tree                      |
                              Stem                 |
                                   Branch          |
                                        Foliage <---
```

Figure 2. Hierarchy for Identification of a Plot and Plot Measurements

This hierarchy allows the project to clearly identify the location and environment of a measurement at the level as low as an individual branch or foliage on a tree. Environmental and socio-economic information can be measured at various levels in this hierarchy.

The geographical unit is a geographical subdivision of a country or region for which socio-economic information may be collected via surveys. Within geographic units individual sites can be identified which have fairly individual physical and physiographic characteristics. These sites are more closely described in terms of these characteristics by climatic and edaphic information. Compartments coincide with existing small stands of a species. Within sites, experiments and demonstration units are established. The basic unit for measuring variables is the plot. A project needs to make the selection of specific experimental designs on the basis of informational needs, availability of land and of time and labor for carrying out the experimentation.

Because each experimental plot or demonstration unit is uniquely linked to soil, site and characteristics of climate, information from these plots in raw or derived form can be associated with information from other sites. The ability to transfer, exchange, and aggregate information from many experiments will provide one of the major benefits for the research network. Scientists will be able to develop improved models for prediction and explanation of components of MPTS systems which should enhance planning and the ability of making better land-use decisions.

CURRENT STATUS OF DATA BASE

The data-base design has been implemented using the KnowledgeMan/2 program. This MIS is based on a relational data-base management system (DBMS) which are becoming increasingly popular and are likely to become the dominant data base in the future. The Project has already generated considerable information. The current status is as follows:

- Over 500 species are represented in the growth data. More than 100 of these have been tested under different ecological conditions. Analysis shows that some 15 species demonstrate major promise with respect to growth and yield.

- More than 200 formal experiments are present.
- In total, about 8000 individual plots of trees are available for analysis.
- 228 soil profile descriptions with 1031 horizon analyses, including chemical and physical characteristics, describe the growth sites.
- There are 894 seed lots described, showing provenance and source information for the seeds used in the different plots.
- Climatic information has been gathered for 561 different meteorological stations, with precipitation and temperature, matching the different sites where the Project operates.
- Experimental site description information is available for 511 sites.
- Socioeconomic information has been collected on selected plantations and on nurseries, and a program of closely monitored demonstration farms has been started to see the impact of tree plantations on the micro-economy of the farm. This information has not yet been entered.

CONCLUSIONS

The development of MIRA is the pioneering work in use of data base and MIS technology in the tropical regions of the world for application of silvicultural research. It is also a first in terms of the cooperative effort carried out by six Central American countries to develop and use standardized data collection procedures for better coordinated research in MPTS. This data base could become the prototype for a proposed Latin American network of forestry research that was the purpose of a recent IUFRO conference in Peru (Rose and Ugalde 1987b).

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A 3/2-POWER-BASED GROWTH MODEL OF MEAN DBH IS LINKED WITH ESTABLISHMENT DENSITY AND MORTALITY TO DEVELOP THINNING GUIDES

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The 3/2-power rule for plant monocultures is applicable to forest plantations. It can be depicted as a relationship between quadratic mean dbh and the number of trees per unit area. Thinning charts using the same variables serve as standard forest management tools for quantifying our thinning knowledge. However, methods of locating guide curves on these thinning charts are not based directly on growth information, and this deficiency serves as a source of controversy about their accuracy and usefulness. Since the necessity to thin is brought on by competition-based mortality, a methodology is developed for the establishment of guide curves on thinning charts which uses a growth model of quadratic mean dbh that is bounded by the 3/2-power rule and linked to a single survival model that covers both the premortality and self-thinning stages of stand development.

ON THE ESTIMATION OF RADIAL INCREMENT BY DIAMETER CLASS USING HORIZONTAL POINT SAMPLING DATA

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The estimation of radial increment by diameter classes using methods suggested for "per-tree" estimates in horizontal point sampling is discussed. The estimator usually recommended for this situation can be viewed as a ratio estimate, where the numerator is an estimate of the sum of the "per-tree" characteristics per acre, and the denominator is an estimate of the number of trees per acre having the desired characteristic. An estimator for the variance of a ratio estimate presented in the text of Cochran (1977) is discussed.

Previous work by Lappi and Bailey (1987) indicates that radial increment estimates made by using unweighted averages of increment cores extracted from trees chosen in a horizontal point sample will generally be positively biased if the estimates are made by initial diameter classes, and the bias can be significant in certain circumstances. This occurs because selection of sample trees in horizontal point sampling is proportional to the square of final diameter, so that trees having large radial increments are more likely to be chosen. Weighted regression techniques and ratio estimates were suggested by Lappi and Bailey (1987) as alternatives to unweighted averages of radial increments obtained from trees selected in a horizontal point sample. These recommendations were based on theoretical considerations and simulation studies conducted by Lappi and Bailey (1987). The current study compares the performance of ratio estimates of radial increment to unweighted averages of radial increment by two-inch dbh classes in a simulated young loblolly pine plantation. The loblolly pine plantation simulator PTAEDA (Daniels and Burkhart 1975) was used to generate a mapped forest stand consisting of Cartesian coordinates and diameters at five year intervals for each tree. The stand was planted at an eight by eight foot spacing, site index 60 (base age 25), unthinned, and slightly less than an acre in size. A FORTRAN program was written which simulated horizontal point sampling cruises in the mapped stand. Sample trees were selected on the basis of their diameters at age 20, but were assigned to two-inch classes on the basis of their diameters at age 15 for radial increment estimation.

One thousand simulated cruises consisting of 30 points each were conducted in the mapped stand. Radial increment estimates were obtained in each two-inch dbh class for each of the 1,000 cruises by using a ratio estimate and through an unweighted average of radial increments obtained from trees selected in point sampling. Averages of 1,000 unweighted average estimates of radial increment were greater than true mean radial increment in dbh classes four through twelve, the percentage differences ranging from about five percent in dbh classes four and six to one and three quarters percent in dbh class twelve. Differences between true five year mean radial increment and averages of 1,000 ratio estimates of radial increment were less than one-half percent in dbh classes four through twelve. Results from dbh classes two and fourteen were difficult to evaluate with the current simulation program since several of the 1,000 cruises did not contain any sample trees in these classes. For the conditions represented by the mapped stand, the ratio estimator appeared to perform better as an estimator of mean radial increment than unweighted averages of radial increments obtained from trees selected by horizontal point sampling.

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PROCEDURES FOR DETERMINING GROWTH TRENDS OF SHORTLEAF PINE AND BLACK OAK IN SOUTHERN ILLINOIS

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This paper reports a study sponsored by the Illinois Department of Energy and Natural Resources to investigate tree growth in southern Illinois. A total of 87 permanent 0.04 ha plots have been established on the Shawnee National forest--50 in natural stands of upland oak and 37 in shortleaf pine plantations. On each plot a dominant black oak or short leaf pine was felled for stem analysis. Soil samples were taken from the A and B horizon on each plot. Increment cores were removed from four dominant trees on each plot and disks were removed at predetermined intervals from the felled tree. Radial growth was measured with a sigma-scan digitizer for the stem analysis.

USING AN EXPERT SYSTEM TO INCORPORATE A GROWTH MODEL INTO A COMPUTER-BASED RED PINE MANAGER'S HANDBOOK

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The red pine manager's handbook has been used extensively as a decision support tool by forest managers in the upper Great Lakes region. A new, computer based edition of this handbook has been developed. The management recommendations are derived by consultation sessions between user and computer, much as a user would consult with a human expert. A stand level red pine growth model is linked to the system to provide yield predictions pertinent to the decision making process. Stocking and yield forecasts are graphically and numerically presented to the user upon request. The management recommendations are derived through a rule-based expert system shell capable of justifying its conclusions to the user in terminology that any forester can understand. This paper describes by example a new way of capturing, organizing, packaging, and distributing forest management knowledge. This computer based red pine manager's handbook serves three functions: (1) help forest managers decide on the best possible treatment recommendations for red pine stands; (2) preserve and distribute the expertise of forest researchers; and (3) furnish an intelligent, computer-assisted training tool for students of forest management.

SISTIM--A NEW MODEL FOR SIMULATING SILVICULTURAL TREATMENTS IN MAINE

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University of Maine

A computer model is presented for calculating per-acre and per-unit cost of producing spruce-fir under a variety of silvicultural systems. Treatment options include site preparation, planting, herbicide release, and precommercial thinning; all costs are specified by the user. Bailey and McNally's tables from Nova Scotia are used to estimate yields on site indices 40-60 (50-year base). Managed stand densities range from 325 (12x12 ft) to 1210 (6x6 ft) stems per acre; natural regeneration without thinning follows a Reineke density index function after reduction for below-normal stocking. Logging costs are specified on a per-tree basis, and can be strongly influenced by piece size. Nomograms illustrate the joint effect of initial density and rotation age on 10 different variables of interest to forest managers.

SIMULATING THE EFFECTS OF DEFOLIATION BY GYPSY MOTH ON FOREST STANDS

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An existing stand model, FORET, has been modified to include the effects of defoliation by gypsy moth on the growth and mortality of individual trees. This stand model may be linked to another model that predicts gypsy moth defoliation, or users may specify defoliation patterns as input to the stand model. Direct effects of defoliation that are simulated include reduced diameter growth and increased mortality rates--especially if other stress factors are acting concurrently--for heavily defoliated trees. Tree species that are less preferred by the gypsy moth may benefit indirectly due to greater light availability during years of defoliation and reduced stand density following gypsy moth outbreaks. Because this model accounts for both direct and indirect effects on individual trees, the influence of gypsy moth defoliation on changes in species composition, stand structure, and stand yield during the course of a rotation can be examined.

THE STAND MANAGEMENT COOPERATIVE

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The Stand Management Cooperative is a research and development organization created to provide a continuing source of high-quality data on the long-term effects of silvicultural treatments and treatment regimes on stand and tree development and wood quality. The program will build a link--now largely missing--between silvicultural and yield research on the one hand and wood quality and utilization research on the other. Emphasis is on forest plantations and management practices of the future. Results will include improved guidelines for stand treatment leading to better management decisions. Gaps in our knowledge exist about effects of treatments in forest plantations, in terms of long-term growth data, interactions of treatments and effects on wood properties. The program in stand management will involve major efforts in plot installation and treatment, data collection and management and data analyses. Primary emphasis in initial program phases will be on defining quantitative effects of silvicultural treatments on volume production, tree dimensions, wood quality and stand dynamics. In future years the program will also provide analyses and interpretations of the data including improved stand simulators, yield estimates and stand treatment guidelines. Work will concentrate on forests west of the Cascade crest in Oregon and Washington and in coastal British Columbia. Initial emphasis will be on Douglas-fir. The Stand Management Cooperative involves forest industry, public land-managing and research agencies, and universities. Currently, 23 organizations participate in the cooperative, including five universities. The program is headquartered at the University of Washington.

PERCENTILE-BASED STOCK TABLES IN THINNED STANDS OF LOBLOLLY PINE

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Stand structure models of naturally-regenerated loblolly pine stands in which thinnings were applied are described in terms of size-class distributions consistent with stand-level prediction. The framework for the size-class distribution models is a system of percentiles. The use of percentiles allows the characterization of both unimodal and multimodal distributions. Percentile-based stock tables require that estimated stand-level merchantable volume be available for allocation to dbh classes. The allocation procedure ensures that each predicted stand-level value equals the value obtained by summing across dbh classes.

Percentiles are developed by considering the stock table as a probability density function using the assumptions that stem dbh is uniformly distributed within a dbh class and stem volume is proportional to the cube of dbh with a distinct proportionality constant for each dbh class. A system of percentiles and stand volume can adequately describe a given stock table.

We will show that systems of percentiles can be estimated from stand characteristics for naturally-regenerated loblolly pine; that impacts of thinnings on these systems can be estimated given some quantitative description of the thinnings; and that growth of these systems can be predicted.

OPTIMAL AGGREGATION OF TREE LIST DATA FOR USE WITH THE STEMS GROWTH PROJECTION MODEL

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The Stand and Tree Evaluation and Modeling System (STEMS) is a growth projection model developed over the last ten years by scientists at the North Central Forest Experiment Station. STEMS is the primary projection tool available to forest managers in the Lake States. Ideally, STEMS should be used with complete sample tree lists from the stand of interest including species, diameter at breast height, crown ratio, tree class, and a trees per acre expansion factor. The overhead required to maintain complete tree lists in applications where hundreds of stands are considered simultaneously for multiple projection periods may lead to unnecessary inefficiencies. An example of such an application is the study of management alternatives on a regional scale. Past research has considered the effects of data aggregation by diameter class and aggregation of whole stands on the precision and efficiency of projections using STEMS. The current study focuses on selecting representative trees from complete tree lists and allocating trees per acre to those representative trees. An optimal set of representative trees is one which provides a projection closest to what the complete tree list would provide.

Forty year projections of quadratic mean diameter using three representative trees from jack pine and aspen populations were nearly identical to the complete tree list projections in several instances. These results and those from projections using different population distributions and numbers of representative trees, as well as an evaluation of results based on size class, will be presented.

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FINDING OUT AND TELLING

Our job at the North Central Forest Experiment Station is discovering and creating new knowledge and technology in the field of natural resources and conveying this information to the people who can use it--in short, "finding out and telling." As a new generation of forests emerges in our region, managers are confronted with two unique challenges: (1) Dealing with the great diversity in composition, quality, and ownership of the forests, and (2) Reconciling the conflicting demands of the people who use them. Helping the forest manager to meet these challenges while protecting the environment is what research at North Central is all about.

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